ERDC/GSL TR-12-3

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Evaluation of Warm-Mix Asphalt Technologies for Use on Airfield Pavements

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Final report

Prepared for US Army Corps of Engineers
Washington, DC 20314-1000

Abstract

From May 2010 to September 2010, researchers of the US Army Engineer Research and Development Center and Mississippi State University evaluated the performance of different warm-mix asphalt (WMA) mixtures for their use for airfield pavements. The performance of mixtures produced using different WMA technologies was compared to the performance of the same mixtures produced at hot-mix asphalt (HMA) temperatures. Studied were permanent deformation, durability, non-load associated cracking, moisture damage, and workability.

Evaluated were Evotherm™ 3G, Sasobit®, and foamed asphalt. Two aggregates, crushed chert gravel and crushed limestone, were used. The base binder was PG 67-22 from a single refinery. Three reclaimed asphalt pavement (RAP) contents were used (0, 25, and 50%) to study the incorporation of higher percentages of RAP in WMA than allowed in HMA.

Results indicated WMA is a viable product for airfield pavement surface mixtures. However, rutting from traffic and moisture-damage susceptibility must be addressed. Adding RAP to the mix could help, but also could reduce low-temperature performance and durability. Findings suggest WMA with RAP is less susceptible to low-temperature performance problems than HMA with RAP. However, it's not possible to translate the lab results for durability or workability to field performance.

Two engineering technical letters (ETLs) and a guide specification were developed from this study. The first, ETL 11-3, was published in August 2011 and provides general information and guidance. The second ETL and the guide specification, both under review, provide more specific guidance on design and construction of airfield pavements using WMA.

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Preface

This report was prepared by the US Army Engineer Research and Development Center (ERDC). Dr. E. Ray Brown, ERDC, Geotechnical and Structures Laboratory (GSL), was manager of the US Air Force Warm-Mix Asphalt Project.

This publication was prepared by personnel of ERDC's GSL, Vicksburg, Mississippi. The principal investigator was Mariely Mejías-Santiago, and Dr. Jesse D. Doyle assisted in preparation of this report. Both Mejías-Santiago and Doyle are from the Airfields and Pavements Branch (APB), Engineering Systems and Materials Division (ESMD), at ERDC. Dr. Isaac L. Howard of Mississippi State University also participated in the research effort and preparation of this report. Other ERDC personnel who assisted include Tim McCaffrey and Kevin Taylor, both of the ESMD Concrete Materials Branch (CMB), and Sahid Rosado of the University of Puerto Rico at Mayagüez. This document was prepared under the supervision of Dr. Gary L. Anderton, Chief, APB; Toney Cummins, Chief, CMB; Dr. Larry N. Lynch, Chief, ESMD; Dr. William P. Grogan, Deputy Director, GSL; and Dr. David W. Pittman, Director, GSL.

COL Kevin Wilson was Commander and Executive Director of ERDC. Dr. Jeffery P. Holland was Director.

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The authors wish to thank Jeremy Robinson and Adam McDaniel, both of the Mississippi Department of Transportation (MDOT), for performing verification testing. Thanks are also extended to Larry Michael of Asphalt Technology Consulting and to MeadWestVaco for donation of Sasobit® and Evotherm™ 3G, respectively, as well as Ergon Asphalt and Emulsions for donating all asphalt for the project. Scott Gluesenkamp of APAC Mississippi and Brent Vander-Meeden of Vulcan Materials are also owed thanks for donating aggregates and helping develop appropriate mix designs.

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (US liquid)	3.785412 E-03	cubic meters
inches	0.0254	meters
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
pounds (force) per foot	14.59390	newtons per meter
pounds (force) per square foot	47.88026	pascals
pounds (mass)	0.45359237	kilograms
square feet	0.09290304	square meters
tons (force)	8,896.443	newtons

1 Introduction

Background

In recent years, the asphalt industry has taken steps to reduce emissions during production and placement of hot-mix asphalt (HMA) by developing and using warm-mix asphalt (WMA). The amount of WMA being used in the United States has quickly increased from the first small test sections placed in 2004 to the point that some state DOTs now allow the use of WMA on projects where HMA is specified (as long as it does not cost more than the bid for HMA.) Many in the industry believe that in very few years, most asphalt mixture produced in the United States will be some form of WMA. However, as WMA continues to be used, much more research is needed to ensure that performance and cost are optimized.

WMA is produced using one of a group of technologies that allow the production and placement temperatures of asphalt mixes to be reduced. These technologies reduce the viscosity of the asphalt and provide complete aggregate coating at temperatures 35 to 100°F lower than typical HMA (Anderson et al. 2008). The reduction in temperatures and improved workability for production and placement of asphalt mixtures provide a number of potential benefits related to sustainable development and improved working conditions. These benefits include:

- reduced fuel consumption
- reduced plant emissions
- use as a compaction aid for stiff mixes
- improved ability to place asphalt pavement in cool ambient temperatures while meeting construction quality requirements
- ability to use longer hauling distances without sacrificing workability during laydown
- ability to incorporate higher percentages of reclaimed asphalt pavement (RAP) without sacrificing quality (Prowell and Hurley 2007).

Much research work involving WMA technologies has been conducted among public and private agencies, and numerous trial sections have been constructed using WMA technologies within the United States (Prowell et al. 2007; Tao and Mallick 2009; Hearon and Diefenderfer 2008). All the experience gained through these projects has helped the asphalt industry achieve a better understanding of the potential for WMA to be an alternative to conventional HMA. It has also helped characterize the behavior of WMA mixes so that the best practices can be identified, and guidance on the use of these technologies can be developed. The National Asphalt Pavement Association (NAPA) published a *Best Practices* manual, which provides important information on the use of WMA technologies for asphalt production (Prowell and Hurley 2007). The most recent publication on WMA was the *Mix Design Practices* from a research project sponsored by the National Cooperative Highway Research Program (NCHRP) (Bonaquist 2011). This publication includes a draft appendix to AASHTO R 35 that provides guidance on special considerations for WMA mix design. Also, some states, including Texas, Virginia, and Florida, have developed guide specifications on the use of WMA for highway construction.

Only a small amount of WMA has been used on airfield pavements (Su et al. 2009). One of the reasons contributing to its limited use is the lack of guidance available for using WMA for airfield construction. A small number of airfield projects have been constructed using WMA, and these have used state department of transportation (DOT) specifications as guidance. Most of the airfield work has been at Logan International Airport in Boston, Massachusetts, which was the first airport in the United States to use WMA. No issues related to poor performance of these airfield projects have been reported so far. The need for guidance on the use of WMA on airfields has increased in the past few years as state DOTs are quickly adopting WMA. In some states it is very likely that WMA technology will be required on all projects in the near future, resulting in the DOD having to use WMA on airfield pavements when paving within those states.

The US Army Engineer Research and Development Center (ERDC) was funded by the US Air Force Civil Engineer Support Agency (AFCESA) to conduct an evaluation of WMA technologies and to develop guide specifications and a US Air Force Engineering Technical Letter (ETL) to provide guidance on using WMA for military airfield pavements. It is expected that the implementation of this guidance will stimulate the use of WMA on military airfield projects. As more projects are constructed using WMA within the DOD, more expertise is gained and more information is available for developing standard practices. The asphalt industry is moving quickly toward the implementation of these technologies for asphalt production, and it is anticipated that soon contractors will mostly be producing WMA. Hence, it is important for the DOD to prepare for a potential transition from HMA to WMA.

Reclaimed Asphalt Pavement

Recently, the price of HMA has increased significantly, primarily due to the increase in cost of asphalt binder. Users are seeking ways to reduce costs of the asphalt mixtures so that pavements can be properly maintained and rehabilitated with the available funds. The most promising method to reduce the cost of asphalt construction is to utilize more reclaimed asphalt pavement (RAP) in the mixes. Many states have specified a maximum amount of RAP to be used in HMA, mainly due to concerns over undesired intrinsic properties of the RAP such as aged binder, poor aggregate quality, and the lack of a proper mix design procedure for HMA mixes with very high RAP contents. States that approve the use of RAP in surface courses generally permit maximum percentages from 10 to 30% RAP. Some states permit even higher percentages from approved RAP sources, but generally require testing of the combined asphalt binder properties. Two primary reasons for this limit on amount of RAP include difficulty in controlling emissions and difficulty in overall workability of the high RAP mixtures.

Research is needed to evaluate ways to utilize higher RAP contents while ensuring continued good performance. There has been significant interest in using WMA technology with mixes containing high RAP content. This combination has the potential to reduce mixture cost, to reduce emissions, to improve performance, to reduce the amount of fuel used during the mixing and placement processes, and to minimize virgin asphalt and aggregate requirements. WMA technology has been shown to improve mixture workability, to reduce aging of asphalt binder during construction, to improve in-place density, and to help to ensure that excessive emissions do not occur. The possibility that high RAP contents and WMA technology can be used simultaneously is very encouraging.

Objectives

The specific objectives of this project were:

- to conduct a literature review of WMA technologies for asphalt production and to use this information to write an ETL to introduce WMA to the US Air Force

- to conduct laboratory testing to evaluate the following performance characteristics of WMA mixes: 1) permanent deformation; 2) durability; 3) non-load associated cracking; 4) moisture damage; and 5) workability
- to evaluate the use of RAP with WMA
- to visit field projects to collect information about current practices and in-place performance and to use this information to assist in development of guide specifications for the use of WMA on airfield pavements
- to write an ETL and a Unified Facilities Guide Specification (UFGS) to provide guidance on the use of WMA for airfield pavements using all of the data and information collected for this project.

Scope

The laboratory component of this project presented in this report investigated the performance of mixtures used near the pavement surface with WMA technologies and with high RAP content. The performance criteria for asphalt mixtures near the surface can be different than that for mixtures used deeper in the pavement and should be considered when evaluating alternative approaches. The specific performance characteristics evaluated in this project were: 1) permanent deformation; 2) durability; 3) non-load associated cracking; 4) moisture damage; and 5) workability. The investigation was performed in the laboratory on mixtures generally meeting material and mixture requirements for airfield pavements. One virgin binder grade, two aggregate types, three warm-mix technologies (in addition to hot-mix control), one RAP source, and three different RAP contents were evaluated.

The research team approached this study with the philosophy that complete blending might not occur between the virgin binder added to the mixes and the aged asphalt in the RAP, especially at warm-mix temperatures. Therefore, the focus of the experimental program was on mixture testing and not on binder testing, though some binder testing was conducted. Also, bottom-up fatigue cracking was not evaluated experimentally, since it was not believed to be problematic for the conditions of interest.

Field projects were visited to collect information regarding mix production, placement and compaction; in-place performance; and any issues related to the use of WMA. Various contractors were interviewed to collect information about the WMA processes and current practices that are used by different states. The data were used only for preparation of ETLs and UFGS guide specifications for WMA as part of the project and are not included in this report.

All the information collected in this project, including the data from the laboratory tests and the information collected during the site visits, was used to develop guidance for the use of WMA on airfield pavements.

Report Organization

This report consists of 5 chapters beginning with an introduction in Chapter 1. Chapter 2 presents the main findings of the literature review. Chapter 3 outlines the experimental program. Results and data analysis are provided in Chapter 4. Finally, Chapter 5 presents conclusions and recommendations from the work. Appendix A contains the raw laboratory test data.

2 Literature Review

Warm-Mix Asphalt Technologies

At the time of this writing there are at least 30 available technologies and/or processes for producing warm-mix asphalt (NAPA 2011). Table 1 lists the current available technologies in the United States. WMA technologies can be classified into three main groups: those using water for foaming, those using a chemical additive or surfactant, and those using some type of organic additive or wax.

Foaming Processes

The processes that introduce water to the hot asphalt rely on the fact that when the water is dispersed in hot mix, it steams, resulting in an expansion of the binder phase and corresponding reduction in the mix viscosity. Foamed asphalt can be produced in three different ways: mechanical injection of water at the plant, adding a material containing internal water, such as zeolites, and using a two-stage process. Once the water is added to the hot asphalt binder, it expands from the conversion of liquid to gas/steam. The small bubbles generated act to reduce the viscosity of the asphalt binder coating on the rock, thereby allowing the mix to be handled and worked at lower temperatures.

Mechanical foaming systems require the installation of a foaming manifold over the existing asphalt injection system on the mixing drum of the plant and installation of corresponding asphalt binder and water feed lines into the manifold. In the process, a small amount of water is introduced through the nozzles, causing the asphalt binder to expand (Prowell and Hurley 2007).

Zeolites are crystalline-hydrated aluminum silicates that are typically sold in granular form with approximately a No. 50 mesh size and contain approximately 20% water by weight. The water is released from the zeolite when heated to 100 °C (212 °F) (Anderson et al. 2008). When water is released in an HMA, it foams the asphalt. The zeolite can be introduced into the asphalt plant by various methods. On a batch plant, it can be manually added directly into the pug mill or automatically using a weight bucket. On a drum plant, the zeolite could be added through the reclaimed

Table 1. WMA processes available in the United States. (adapted from Bonaquist, 2011).

Name	Process/Additive	Company
Accu-Shear Dual Warm Mix Additive System	Foaming system	Stansteel
Adesco/Madsen Static Inline Vortex Mixer	Foaming system	Adesco/Madsen
Advera	Zeolite	PQ Corporation
AQUABLACK	Foaming system	Maxam Equipment Company, Inc.
AquaFoam	Foaming system	Reliable Asphalt Products
Asphaltan –B	Montan wax	Romonta
Aspha-min	Zeolite	Eurovia
BituTech PER	Chemical additive	Engineered Additives LLC
Cecabase RT	Chemical additive	Arkema Group
Double Barrel Green	Foaming system	Astec, Inc.
ECOBIT	Unspecified Additive/Process	All States Materials Group
Eco-Foam II	Unspecified Additive/Process	AESCO/Madsen
Evotherm ET	Emulsion	MeadWestvaco
Evotherm DAT	Chemical Additive	MeadWestvaco
Evotherm 3G	Chemical Additive	MeadWestvaco
Green Machine	Foaming system	Gencor Industries
HGrant Warm Mix System	Unspecified Additive/Process	Herman Grant Company
LEA-CO	Unspecified Additive/Process	Advanced Concepts Engineering Co
Licomont BS-100	Fatty acid derivative	Clariant
Low Emission Asphalt	Sequential coating using wet fine aggregate	McConnaughay Technologies
Meeker Warm Mix Asphalt System	Foaming system	Meeker Equipment
Qualitherm	Chemical additive	Iterchimica
Rediset WMX	Chemical additive	Akzo Nobel
Sasobit	Fischer Tropsch wax	Sasobit
SonneWarmix	Wax	Sonneborn Products
Terex Warm Mix Asphalt	Foaming system	Terex Roadbuilding
Thipoave	Sulfur	Shell
TLA-X	Trinidad Lake Asphalt plus modifiers	Lake Asphalt of Trinidad and Tobago
Tri-Mix Warm Mix Injection	Foaming system	Tarmac Inc.
Ultrafoam GX	Foaming system	Gencor Industries, Inc.
WAM Foam	Soft binder followed by hard foamed binder	Kolo Veidekke, Shell Bitumen

asphalt pavement (RAP) collar or by using a specially built calibrated vane feeder to control the quantity of material pneumatically blown into the drum (Prowell and Hurley 2007).

The two-stage process consists of a two-stage addition of the asphalt binder. In the first stage, the aggregate is coated with a very soft binder (flux) that controls the minimum mixing and compaction temperatures for the mixture. In the second stage, a harder binder is added with the addition of a very small amount of water. The water foams the hard asphalt, allowing the expanded binder to coat the aggregate. This technology requires storage for the two different binder grades as well as two heated asphalt lines into the mixing chamber.

Organic Additives or Waxes

Organic additives such as wax cause a decrease in the asphalt binder's viscosity when heated above the melting point, allowing mixing and coating. The increased workability at mixing and compaction temperatures acts to improve compactability. These additives can be incorporated at the asphalt terminal or in the contractor's tank by circulation without requiring high-shear blending. Other organic additives are referred to as "intelligent fillers," as they provide improved flow at mixing and compaction temperatures and added stiffness at temperatures below the melting point.

One of the most commonly used waxes in the United States and around the world is Sasobit®. Sasobit® is an organic, hydrocarbon-based wax produced by the Fischer-Tropsch process (SasolWax 2004). Manufactured by Sasol Wax GmbH, it has been used in Europe for a number of years and has performed well in service (D'Angelo et al. 2008). Above its melting point of 100 °C (212 °F), Sasobit® reduces the measured asphalt viscosity that permits reduction of the mix temperature and promotes asphalt mixing and compaction. Below its melting point, Sasobit® solidifies into a lattice structure that stiffens the asphalt binder (SasolWax 2004; Mallick et al. 2008). The reduction in mix temperature with Sasobit® is thought to reduce binder aging, which will help compensate for its stiffening effects (Hurley and Prowell 2005).

Chemical Additives or Surfactants

Chemical additives are used to produce WMA by reducing the binder's viscosity. These additives can be injected at the mixing plant or asphalt terminal and can achieve lower production temperatures than foaming processes. In addition, it is thought that some of the additives can reduce mixture stripping.

Evotherm™ 3G is one of the most commonly used chemical additives for warm-mix asphalt production. It is a proprietary formula liquid asphalt additive designed to improve coating, mixing, workability, and compaction of asphalt mixtures (MeadWestvaco 2011)

WMA Projects

The first trial section of WMA in the United States was placed in February 2004 (Brown 2010). Since then, millions of tons of WMA have been placed. Several states, including Texas, Alabama, and Indiana, have approved the use of WMA on state roads and use it as a standard process. Furthermore, some states allow the use of WMA on any project that was bid for HMA. However, the use of WMA for airfield paving has been limited. Paving trials have been reported at Ted Stevens Anchorage International Airport and Elmendorf AFB, Alaska.

In 2008, Boston's Logan International Airport was the first airport in the United States to use WMA on runway rehabilitation when 26,000 tons of WMA were paved on Runway 4R/22L. Good performance and energy savings were accomplished with this project. Therefore, in 2009, a larger project (55,000 tons) was constructed at Logan International Airport for rehabilitation of Runway 9-27, where the ease of WMA compaction was demonstrated along with reduced emissions and energy savings (Lisican, 2010). WMA was also used in the extension of Taxiway Delta at Logan (40,000 tons). These projects used Sasobit technology and also incorporated from 15 to 20% RAP.

In addition, user agencies and producers in various states are working together to conduct research to evaluate WMA technologies. Individual state trial projects and national research projects (National Cooperative Highway Research Program [NCHRP] 9-43, 9-47, 9-49) have been carried out to address WMA mix design, performance testing, moisture susceptibility, production, construction, and field performance (TRB 2011b; Bonaquist 2011). Also, the National Asphalt Pavement Association (NAPA), FHWA, the American Association of State Highway and Transportation Officials (AASHTO), and researchers formed a national technical working group to evaluate the performance of WMA technologies, quantify environmental benefits, develop performance specifications, provide technical guidance, and disseminate information.

RAP in HMA

Some research studies have indicated that the performance of mixes containing RAP is equal to and in some cases better than that of conventional mixes (Brown 1984; Meyers et al. 1983; and Kandhal et al. 1995). The properties of recycled mixes are mainly influenced by the properties of the aged RAP binder and the amount of RAP in the mix. The amount of RAP used in a mix depends on the type of plant used for preparing the mix and also on environmental considerations (Kandhal et al. 1995). Several studies have been dedicated to evaluating performance characteristics of recycled asphalt mixes. Generally, the studies focus on determining the effect of RAP content on mixing efficiency, permanent deformation, non-load associated cracking, and moisture damage. Huang et al. (2005) analyzed the blending process of RAP with virgin mixture. The study considered three different RAP contents: 10, 20, and 30%. Results from this study indicated that, regardless of the RAP content, mechanical blending affected only a small portion of aged asphalt binder in RAP. Only a small portion of aged asphalt in the RAP actually participated in the remixing process. Other portions formed a stiff coating around RAP aggregates, where the RAP acted as a “composite black rock” that is desirable to improve the performance of the hot-mix asphalt mixture.

Very few studies have addressed the use of high RAP mixes for surface layer mixes, and this has been found to be unacceptable for HMA. High RAP mixes are mainly used for base or subbase pavement layers. In these cases, rejuvenators, modifiers, or softer virgin binders are used to counteract the stiffening of the mix with the addition of the RAP material. Ozer et al. (2009) conducted a study to evaluate the RAP binder contribution to the mix stiffening by testing mixes with different RAP contents (0, 20, and 40%) and measuring the mixes’ complex moduli and fracture energy. Their results showed that up to 20% RAP content does not affect the end mix, but 40% RAP content causes a significant increase in complex moduli compared to 0 and 20% RAP mixes. They concluded that using softer virgin binders allowed for the mixes to offset the increase in stiffness due to the presence of 40% RAP in the HMA.

Mixture Performance

Permanent Deformation

Prowell et al. (2007) showed that warm-mix asphalt placed on the National Center for Asphalt Technology (NCAT) test track provided good resistance to rutting when subjected to high levels of truck traffic. Other studies (Tao and Mallick 2009; You and Goh 2008; Su et al. 2009; Kanitpong et al. 2008) have shown that WMA is more susceptible to rutting in laboratory tests than HMA is. The lower mixing temperature for these WMAs is likely one of the causes of the higher laboratory rutting with respect to HMA, because the binder is less susceptible to volatilization and oxidation at lower temperatures.

Gui-ping and Wing-gun (2006) evaluated the effect of RAP on the permanent deformation of foamed asphalt mixes by using the dynamic creep test. They found that increasing the RAP content helps to reduce permanent deformation. There have been many other studies that show adding RAP reduces the susceptibility to rutting due to the stiffening effect of the aged binder in the RAP.

Low-Temperature Cracking

Low-temperature cracking of asphalt pavements is a widespread and costly problem over much of the United States and Canada (Haas and Phang 1988). The combined effects of temperature and properties of the bituminous component have been identified as the primary factors for low-temperature cracking (Hass and Phang 1988; Roque et al. 1995; Kim and El Hussein 1995). Specifically the temperature-stiffness relationship of the asphalt binder has been identified as the most important factor (Jung and Vinson 1993).

Low-temperature cracking does not seem to be a concern for WMA mixes. The lower mixing temperature is thought to minimize any change in the low-temperature grade of the binder. On the other hand, mixes containing high RAP percentages (above 40%) have been shown to be stiff and more susceptible to low-temperature cracking (Ozer et al. 2009; Li et al. 2008). The interaction of these two effects in high RAP-WMA mixes has not been extensively investigated. Based on past observations it is hypothesized that the blended binder may age slower than that for a new binder, since the RAP binder has already aged and is not expected to change much in the future. Therefore, the amount of future thermal cracking may be reduced for high RAP-WMA, since the binder is close to the original grade and may not be expected to age at the same rate or as much as a virgin binder.

Several methods are available to evaluate the effect of binder properties on the resistance of low-temperature cracking (Vinson et al. 1989). Zofka et al. (2004) conducted an investigation to determine the possibility of obtaining the RAP binder properties required for use with blending charts by using a relatively simple test performed directly on the RAP mixture. The objectives were to find a test that would avoid the use of the extraction and recovery and the use of very expensive mixture testing. They proposed a new method which consists of obtaining mixture stiffness by performing bending beam rheometer (BBR) tests on beams of asphalt mixture cut from laboratory-prepared cylindrical specimens. Based on the stiffness of the mixture determined with the BBR, the stiffness of the asphalt binder component is then back-calculated using the Hirsch Model, which is based on the theory of composite materials. The method appeared to be promising and, compared to the traditional indirect tensile test method, this method is simpler, less expensive and requires less equipment to take measurements (i.e., there is no need for extensometers placed on the test specimens). This method also uses smaller samples that can be utilized in studying aging effects across the depth of the asphalt layers.

Durability Test

The Cantabro durability test has been used as a screening tool for Porous Friction Course (PFC), also known as Open-Graded Friction Course (OGFC), asphalt mixtures. It has been used as a relative measure of potential for raveling and durability problems in OGFC and PFC but has not been widely used for conventional dense-graded asphalt mixtures (Doyle and Howard 2011a; Watson et al. 2003). For un-aged OGFC mixture specimens, a maximum aggregate loss of 20% has been recommended (Watson et al. 2004). Several researchers have found the Cantabro test to be sensitive to changes in binder properties, especially between neat and polymer-modified binders (Watson et al. 2004; Alvarez et al. 2008; Kraus 2008).

Moisture Susceptibility

Some laboratory studies have shown that WMA has higher moisture sensitivity than typical HMA (Kanitpong et al. 2008; Su et al. 2009). One concern is that the lower mixing and compaction temperatures of WMA can result in incomplete drying of the aggregate leaving trapped moisture that may cause damage. These lower mixing temperatures can also result in less hardening of the asphalt, thus reducing adhesion to the aggregate particles. Xiao et al. (2009) conducted a laboratory study to examine WMA moisture damage with moist aggregates. The study included two moisture content percentages (0% and 0.5% by dry aggregate mass), two WMA additives (Asphamin and Sasobit®), and three aggregate sources. Test results indicated that the use of WMA additives did not significantly alter the dry, indirect tensile strength and toughness values. It was also reported that the deformation resistance and Tensile Strength Ratio (TSR) values decreased with the increase in aggregate moisture content.

Prowell et al. (2007) evaluated moisture susceptibility of three WMA mixtures using indirect tensile strength based on ASTM D4867 and the Hamburg wheel-tracking device. Results indicated that Asphamin decreased the TSR to below 0.8. Sasobit® and Evotherm TSR results depended on aggregate type. Sasobit® increased TSR for limestone aggregates and decreased TSR for granite aggregates, while Evotherm increased the TSR for granite and decreased TSR for limestone.

Kvasnak et al. (2009) evaluated the moisture susceptibility of laboratory- and plant-produced WMA mixes as part of a field demonstration project in Alabama. Results indicated that the laboratory-produced WMA was more susceptible to moisture damage than the plant-produced mix. The HMA exhibited more favorable TSR values than the WMA; however, most of the WMA specimens met Superpave moisture susceptibility criteria.

Recently, Kvasnak et al. (2010) compared the performance of mixes produced using the Gencor Green Machine Ultrafoam GX to a control HMA with regard to moisture susceptibility, permanent deformation, and fatigue cracking. Both mixes were prepared at the same production facility using the same aggregate gradation, liquid asphalt, and asphalt content. It was reported that the WMA mixtures had lower TSR values and, hence, might be more susceptible to moisture damage than HMA mixtures. However, it was suggested that the resistance of WMA mixtures to moisture could be increased, if desired, by using anti-strip agents.

Li et al. (2004) evaluated the moisture susceptibility of RAP mixes. The study investigated the effect of RAP type and percentage on asphalt mixture properties. Three RAP percentages (0, 20, and 40%) were used. Results indicated an increase in tensile strength and a decrease in TSR as the RAP percentage increased.

Zaniewski and Viswanathan (2006) reported on use of the AASHTO T 283 test method for three mixtures of known good field performance. The 16-hour loose mix aging at 60 °C required by the test method was included as part of the specimen preparation method; conditioning by vacuum saturation alone and by one freeze-thaw cycle in addition to vacuum saturation was evaluated. Results indicated that test method was not sensitive to saturation level or to inclusion of a freeze-thaw cycle as part of the conditioning protocol. The TSR results indicated that all three mixtures were moisture sensitive, leading the authors to conclude that "TSR is not a reliable indicator of field performance" for the mixtures tested.

Azari (2010) conducted wet HLWT at 50 C and TSR testing of two mixtures of general low- and high-moisture susceptibility and observed that HLWT results were more consistent with observed field performance of the mixtures. The TSR results predicted that both mixes were acceptable with regards to moisture susceptibility. Precision estimates for AASHTO T 283 were produced based on the work done by Azari (2010). Single operator precision for TSAR was found to be 0.093 and multilaboratory precision was determined to be 0.247 (TRB 2011a). This is problematic since the allowable multilaboratory precision is essentially the same as the range of acceptable TSR values for military specifications of greater than 0.75.

Workability

One purported benefit of warm-mix asphalt is the increased workability at lower (and at conventional) compaction temperatures. Workability can be defined from a field perspective as the asphalt mixture property that describes the ease with which the asphalt mixture can be placed, worked by hand, and compacted to the desired density (Bennert et al. 2010).

Several methods have been developed to study the workability of asphalt mixes, including gyratory compactors equipped with devices that measure the force required to apply the gyratory compaction angle and devices that measure the torque required to move a blade or paddle through a loose mixture sample. Gudimettla et al. (2003) developed a prototype workability device at the NCAT that functioned by measuring the torque required to rotate a paddle submerged in a bucket of asphalt mixture at 15 revolutions per minute (RPM). Data were collected for a range of temperatures as the mixtures sample was allowed to cool. A laboratory experiment conducted with the device for a variety of mixtures showed that the device was sensitive to aggregate type, binder type, and temperature.

Recently, Bennert et al. (2010) evaluated various methods to quantify workability for WMA. Of the six methods investigated (three binder and three mixture), the most rational rankings of data were obtained by binder lubricity testing, and workability measurements with a device similar to the NCAT Prototype device and air voids of specimens compacted with the Marshall hammer. Austerman et al. (2009) evaluated workability of WMA containing 10 to 25% RAP and observed improved workability with respect to HMA. Other researchers (Mallick et al. 2007; Tao and Mallick 2009) have evaluated workability of 100% RAP mixtures with WMA additives for in-place recycling applications and found improved workability relative to mixtures without the WMA additives.

3 Experimental Program

An experimental program was developed to investigate performance issues related to WMA mixtures; in addition, the use of high-RAP contents was evaluated. The five performance characteristics evaluated in this study were: 1) permanent deformation; 2) durability; 3) non-load associated cracking; 4) moisture damage; and 5) workability. Permanent deformation, durability, and non-load associated cracking tests were conducted at the Asphalt Laboratory of the Civil and Environmental Engineering Department of Mississippi State University. Moisture damage and workability tests were conducted at the Materials Test Center (MTC) of the ERDC. The following sections describe the experimental design, materials, and test methods in this study.

Experimental Design

For this study a full factorial experimental design was conducted that encompassed factors of asphalt mixture type (4 levels), aggregate type (2 levels), and RAP content (3 levels) for a total of 24 asphalt mixtures as shown in Table 2. The mixtures are identified throughout this report by the numbers 1 to 24. The four asphalt mixtures types investigated were conventional HMA used as a control, WMA produced with Sasobit®, WMA produced with Evotherm™ 3G, and WMA produced with foamed asphalt. The aggregate types were limestone and crushed chert gravel. Three levels of RAP content were evaluated: 0% RAP as currently required for airfield surface mixtures; 25% RAP, which is allowed for shoulders and non-surface pavement layers of airfields (USACE 2010); and 50% RAP. Although 50% RAP is higher than currently allowed, it was included to evaluate the potential for WMA technologies to permit high RAP contents.

Mixture tests were selected for each performance category evaluated. Permanent deformation (rutting) was evaluated with the Asphalt Pavement Analyzer (APA). Durability was evaluated with the Cantabro test. Non-load associated cracking (thermal cracking) was evaluated using the BBR mixture test. Susceptibility to moisture damage was evaluated with the TSR test. The effects of varying mixing and compacttion temperatures on moisture susceptibility were also investigated using the TSR test. Workability was assessed with the NCAT Workability Device. Table 3 summarizes the testing conducted for HMA and WMA mixtures.

Table 2. Experimental design and mixture identification.

Aggregate Type	RAP Content	Aggregate Blend	Mixture Type and Identification Number			
			HMA	WMA-Sasobit®	WMA-Evotherm™	WMA-Foam
Limestone	0%	LS-1	1	2	3	4
	25%	LS-2	5	6	7	8
	50%	LS-3	9	10	11	12
Crushed Gravel	0%	GR-1	13	14	15	16
	25%	GR-2	17	18	19	20
	50%	GR-3	21	22	23	24

Note: LS means limestone and GR means gravel; they indicate what the majority of the virgin aggregate in the gradation consisted of.

Table 3. Mixture production temperatures and testing replication.

Mixture Type	Testing Category	Production Temperature Mix / Compact (°C) and Replication		
		160 / 146	146 / 132	130 / 116
HMA	APA	3	---	---
	Cantabro	3	---	---
	BBR -06 C	2	---	---
	BBR -12 C	2	---	---
	TSR	1[a]	---	---
	Workability[b]	2	---	---
WMA	APA	---	---	3
	Cantabro	---	---	3
	BBR -06 C	---	---	2
	BBR -12 C	---	---	2
	TSR	1[a]	1[a]	1[a]
	Workability[b]	---	---	2

Note: Dashes indicate combinations that were not tested.

a) One TSR replicate represents three dry specimens and three conditioned specimens.

b) Workability testing conducted on limestone mixtures only (mixtures 1 to 12).

Materials

Aggregate Blends

Figure 1 provides the six gradations used in the study, and Table 4 provides the types and percentages of the aggregates used. All gradations had a nominal maximum aggregate size (NMAS) of 12.5 mm. The gradations were designed to meet the Unified Facilities Guide Specification UFGS-32 12 15

Figure 1. Gradations of aggregate blends tested.

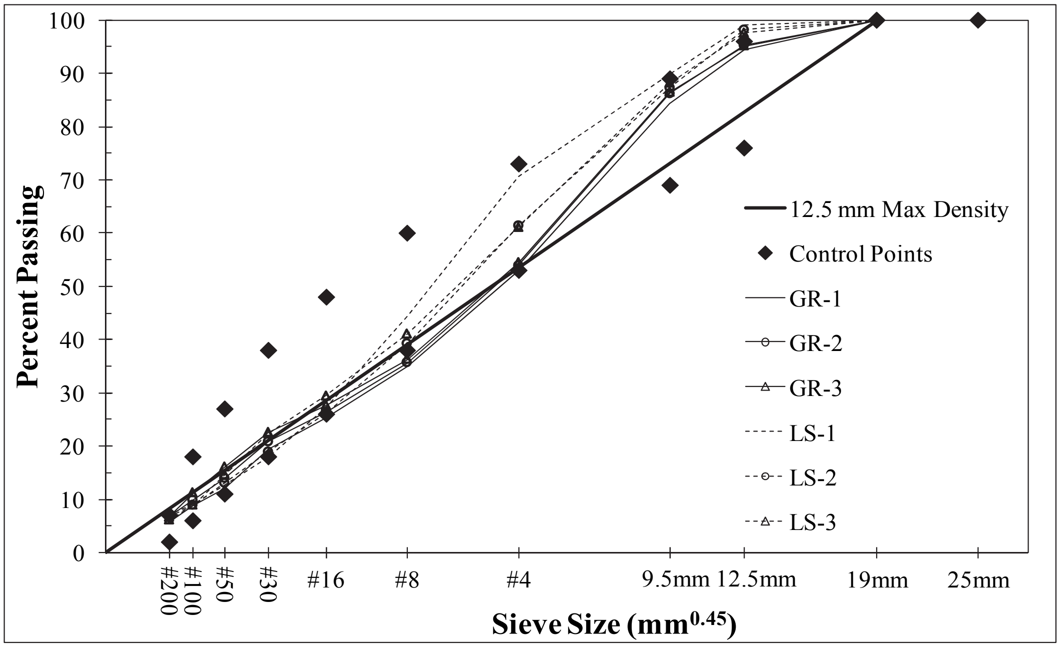


Table 4. Properties of aggregate blends tested.

Component	Aggregate Blend[a]					
Percentages	LS-1	LS-2	LS-3	GR-1	GR-2	GR-3
RAP	---	25	50	---	25	50
Limestone	100	75	50	8	6	5
Gravel	---	---	---	81	63	44
Sand	---	---	---	10	5	---
Hydrated Lime	---	---	---	1	1	1
Combined Aggregate Properties						
G_{sb}[b]	2.692	2.643	2.603	2.419	2.430	2.436
G_{sa}[c]	2.774	2.730	2.687	2.612	2.607	2.602
Absorption (%)	1.1	1.2	1.2	3.1	2.8	2.8
CAA[d] (%)	100	98	97	93	94	95
Coarse U_R[e] (%)	47.3	47.3	47.3	46.2	46.3	46.2
F&E[f] (%)	2	2	1	1	1	1

a) LS refers to limestone and GR refers to gravel and they indicate the major virgin aggregate component of the gradation.

b) Bulk Specific Gravity

c) Apparent Specific Gravity

d) Coarse aggregate angularity (two or more fractured faces) performed according to ASTM D 5821 using the particle count method.

e) Coarse aggregate un-compacted voids content performed according to AASHTO T 326 Method C. Values are those for virgin aggregate only; insufficient extracted RAP aggregate was available to perform the test.

f) Flat and elongated particles performed according to ASTM D 4791 using a 5:1 ratio.

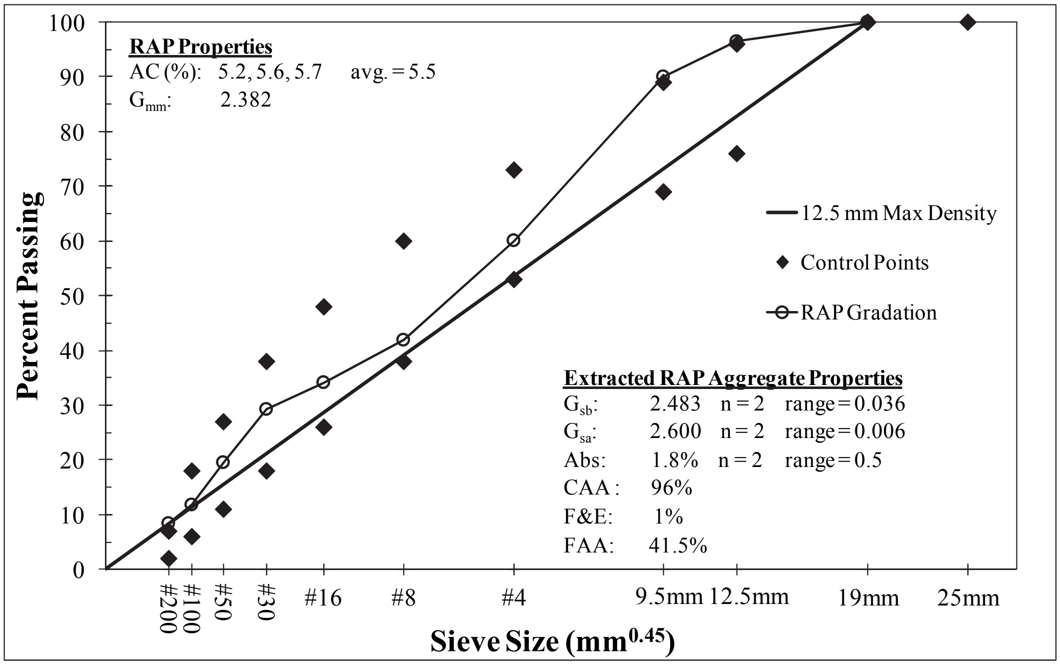
(United States Army Corps of Engineers, 2010) job mix formula (JMF) requirements for airfields. Slight gradation deviations (e.g., for the GR-1 gradation, the 1.18 mm sieve (#8) was 3% outside the USACE specification) occurred in a few instances to preserve uniformity between gradations for performance comparisons while using substantial amounts of RAP. However, these deviations from the specifications are within acceptable tolerance limits. Milling of pavements to produce RAP increases the fines content, which poses difficulty in meeting the specification because the higher fines content made it more difficult to meet the requirements for voids in mineral aggregate (VMA).

The three gravel gradations are typical of the types of aggregate blends used in Mississippi; natural sand and limestone fine aggregate are used in combination with crushed gravel coarse aggregate to produce desired gradations. Every effort was made to minimize the amount of non-gravel virgin aggregate used in blends GR-1 to GR-3. The natural sand used in blends GR-1 and GR-2 was obtained from the same source as the crushed gravel. The water absorption of the gravel blends is markedly higher than for the limestone blends as seen in Table 4. One percent hydrated lime was added to each gravel blend as anti-strip; no hydrated lime or other anti-strip was put into the limestone blends as they are not typically associated with stripping problems. Percentage of fractured faces, un-compacted voids content of coarse aggregate, and percentage of flat and elongated particles were estimated for each aggregate blend based on the percentage of each aggregate in the gradation; the data are presented in Table 4.

RAP Properties

The primary source of RAP is from highway pavements. The RAP source used for all mixes in this study was obtained from surface milling of an interstate highway (I-55) in central Mississippi. Figure 2 provides the extracted RAP aggregate gradation and key properties of the RAP and extracted aggregate. Properties of the RAP were obtained from three different laboratories: 1) Mississippi State University (MSU); 2) United States Army Engineer Research and Development Center (ERDC); and 3) Mississippi DOT Central Materials Laboratory. Asphalt content was determined at MSU and ERDC according to ASTM D 2172 Method A using trichloroethylene as the extraction solvent. Asphalt content was determined at MDOT according to AASHTO T 308 Method A. Gradation analysis of extracted aggregate was conducted at all three laboratories; properties of solvent extracted aggregate were tested at ERDC and MSU. Visual

Figure 2. Physical and gradation properties of RAP.



examination and categorization of clean extracted aggregate indicated that approximately 9% by mass of the material retained on the 1.18 mm sieve consisted of limestone, and the remainder was crushed gravel and natural sand. The hump in the aggregate gradation shown in Figure 2 is an indicator that the aggregate contains a significant amount of natural sand.

As part of a different study described in Doyle and Howard (2011b), experiments have been performed with this RAP source to investigate whether the RAP would absorb any additional asphalt when recycled into a high RAP mix design. Based on the results it was concluded that a negligible amount of additional asphalt is absorbed by the RAP aggregate, whether asphalt from the RAP or virgin binder added to the RAP. The values of absorbed asphalt (P_{ba}) calculated for the RAP appear to be too high; this is likely due to difficulty in accurately measuring the bulk specific gravity (G_{sb}) of the extracted aggregate.

The research team felt that absorbed asphalt within the RAP aggregate would not contribute to blended properties of the 25 and 50% RAP mixtures. For determination of the RAP binder grade, an attempt was made to extract the asphalt surface film from the RAP and to leave the majority of the absorbed asphalt intact. Three washes of trichloroethylene solvent were used with a 45-minute soak period for each wash. Roughly 3.6% asphalt was extracted from the RAP using the three-wash procedure;

as the total asphalt content (AC) was 5.5%, approximately 1.9% asphalt remained in the RAP. Less than all of the RAP surface asphalt was extracted using the three-wash procedure. The continuous PG binder grade of the recovered surface asphalt was estimated to be PG 117.8+1.7; the high pass/fail temperature was extrapolated from test data at lower temperatures. This rough estimate of the RAP binder grade is provided as a point of reference only and is not used for any calculations. The outer portion of the binder is expected to have aged more than the absorbed asphalt. Therefore, it is expected that the grade of the recovered asphalt would have been less if all of the asphalt had been extracted.

Volumetric Properties

Table 5 provides the Superpave designed volumetric properties of the 24 mixtures investigated. In general, both the total and effective asphalt contents of the mixtures containing limestone virgin aggregate are lower than those containing gravel aggregate. This is reasonable due to the higher specific gravity and lower asphalt absorption of the limestone aggregate relative to the gravel aggregate. For the 25% RAP limestone mixes the ratio of virgin asphalt to asphalt contributed by the RAP is roughly 75:25. For the 50% RAP limestone mixes the ratio is roughly 55:45. For the gravel mixes the ratios are roughly 80:20 and 60:40 for the 25% and 50% RAP mixes, respectively.

For the 50% RAP limestone mixtures note the increase in the effective asphalt content (P_{be}) between the hot mix (Mix 9) and the warm mixes (Mixes 10 to 12). Also note the large reduction in total asphalt content that occurs in the 0% RAP gravel mixes from the hot mix (Mix 13) to the warm mixes with additives (Mixes 14 and 15). A portion of this reduction is thought to be due to reduced absorption of asphalt binder by the gravel aggregate at lower short-term aging temperatures. It can be seen in Table 5 that P_{ba} for Mixes 14 and 15 is 0.2% less than for Mix 13. A 0.4% reduction in P_{be} is also seen for Mixes 14 and 15 compared to Mix 13.

For the 50% RAP gravel mixtures, an increase in total and effective asphalt content is noted in Mixes 22 and 23 compared to Mix 21. This is thought to be partially due to reduced rejuvenating of the RAP surface asphalt at the lower temperature compared to the hot mix; additional virgin binder is therefore required to achieve compaction. For example, the total asphalt content of Mix 14 is 6.0%, and the total asphalt content of Mix 22 is 7.0%. The two aggregate gradations are of nearly identical shape, and Mix 22

Table 5. Volumetric properties of designed mixtures.

Mix	AC (%)								
No.	Virgin[a]	RAP[b]	Total	G_{mm}[c]	G_{se}[d]	P_{be}[e]	P_{ba}[f]	VMA[g]	VFA[h]
1	4.9	0.0	4.9	2.545	2.754	4.1	0.9	13.9	69.3
2	4.9	0.0	4.9	2.545	2.754	4.1	0.9	14.1	68.5
3	4.8	0.0	4.8	2.553	2.759	3.9	0.9	14.0	65.9
4	5.0	0.0	5.0	2.537	2.749	4.3	0.8	14.0	72.1
5	3.9	1.4	5.3	2.495	2.711	4.4	1.0	13.6	75.3
6	3.9	1.4	5.3	2.495	2.711	4.4	1.0	13.7	74.8
7	3.9	1.4	5.3	2.495	2.711	4.4	1.0	13.8	74.2
8	3.9	1.4	5.3	2.495	2.711	4.4	1.0	13.7	74.8
9	3.1	2.8	5.9	2.437	2.665	5.0	0.9	15.6	73.1
10	3.3	2.8	6.1	2.430	2.665	5.2	0.9	16.5	70.9
11	3.3	2.8	6.1	2.430	2.665	5.2	0.9	16.4	71.8
12	3.3	2.8	6.1	2.430	2.665	5.2	0.9	15.8	74.8
13	6.6	0.0	6.6	2.262	2.471	5.8	0.9	16.0	76.2
14	6.0	0.0	6.0	2.269	2.458	5.4	0.7	15.9	71.1
15	6.0	0.0	6.0	2.269	2.458	5.4	0.7	16.1	70.1
16	6.5	0.0	6.5	2.261	2.466	5.7	0.8	16.0	75.7
17	5.2	1.4	6.6	2.286	2.501	5.5	1.2	15.7	74.1
18	5.0	1.4	6.4	2.276	2.480	5.6	0.9	15.7	75.6
19	5.1	1.4	6.5	2.273	2.480	5.7	0.9	16.0	75.2
20	4.9	1.4	6.3	2.286	2.489	5.3	1.0	15.6	72.5
21	4.0	2.8	6.8	2.293	2.516	5.5	1.4	15.6	75.2
22	4.2	2.8	7.0	2.286	2.515	5.7	1.3	15.8	77.5
23	4.3	2.8	7.1	2.283	2.515	5.8	1.3	16.4	75.4
24	3.9	2.8	6.7	2.291	2.510	5.5	1.2	15.8	73.8

Note: Mixtures 1-12 are limestone mixtures and 13-24 are gravel mixtures. All mixtures at 4% air voids and compacted with 75 gyrations.

a) Virgin binder added to the mix, %

b) RAP asphalt contributed to mix assuming 100% utilization of RAP asphalt, %

c) Maximum specific gravity

d) Effective specific gravity of aggregate

e) Effective asphalt content, %

f) Absorbed asphalt, %

g) Voids in the mineral aggregate, %

h) Voids filled with asphalt, %

contains just more than half the amount of virgin gravel aggregate that Mix 14 does. It has been shown that the RAP aggregate absorbs a negligible amount of additional virgin asphalt and that the virgin aggregate absorbs less asphalt at a lower short-term aging temperature. The additional 1.0% of total asphalt can therefore be at least partly explained by a reduction in rejuvenation of the RAP surface asphalt. Most of the variation in test properties could be due to normal variation in sampling, mixing, and testing.

Binder and Warm-Mix Properties

The base binder for all mixtures was PG 67-22 from a single refinery. The typical high, intermediate, and low PG temperatures of the base binder were 68.7, 23.5, and -24.0 °C respectively. Sasobit® was added at a rate of 1.5% of virgin binder mass and Evotherm™ 3G was added at a rate of 0.5% of virgin binder mass. Water added during foaming was 2% of binder mass and was not considered part of the binder mass for calculation of asphalt content.

Table 6 provides asphalt content and PG pass/fail temperatures of recovered asphalt for Mixes 1 to 12. Binder properties were only evaluated for the limestone aggregate (lowest absorption) mixes, since the same RAP was used for all mixes and the effects of virgin aggregate type were assumed to be minor. The testing on the recovered asphalt was performed assuming that the recovered asphalt was already aged. Therefore, there was no need to test after running the Rolling Thin Film Oven (RTFO) test or the Pressure Aging Vessel (PAV) test.

Going from 0% RAP to 25% RAP shows that the high-temperature property increased by approximately 8 degrees. This increase in RAP only changed the low-temperature properties by approximately 3 degrees. Going from 0% RAP to 50% RAP changed the high-temperature properties by approximately 20 degrees, whereas it only changed the low-temperature properties by approximately 8 degrees. Hence, adding RAP favorably affects the high-temperature properties (provides more rut resistance) much more than it adversely affects the low-temperature properties (provides less resistance to thermal cracking). Potentially the aged binder may have reduced the temperature susceptibility, resulting in an increase in PG grade at high temperatures and less change at low temperatures. However, specific conclusions cannot be made with the available data, and further research would be needed to investigate this issue.

Table 6. Extraction and recovered asphalt data for mixtures 1 to 12.

RAP (%)	Mix No.	Total Asphalt Content (%)	Pass / Fail Temperature (°C)		
			High	Intermediate	Low
0	1	4.7	73.0	19.3	-27.5
	2	4.8	70.3	20.7	-27.0
	3	4.7	66.0	16.4	-30.1
	4	5.2	68.8	18.3	-27.7
	Average Temperature (°C)		**69.5**	**18.7**	**-28.1**
	Range of Temperatures (°C)		**7.0**	**4.3**	**3.1**
25	5	5.1	80.5	23.3	-24.9
	6	5.2	78.0	24.7	-23.7
	7	5.0	73.4	17.9	-28.2
	8	5.2	78.8	24.0	-25.4
	Average Temperature (°C)		**77.7**	**22.5**	**-25.6**
	Range of Temperatures (°C)		**7.1**	**6.8**	**4.5**
50	9	Not Available	85.8	28.7	-21.9
	10	5.7	88.2	29.1	-22.0
	11	6.1	96.0	31.5	-14.3
	12	5.7	88.2	29.2	-20.7
	Average Temperature (°C)		**89.6**	**29.6**	**-19.7**
	Range of Temperatures (°C)		**10.2**	**2.8**	**7.7**

Note: The high pass / fail temperature was determined based on a 2.20 kPa min criteria.

WMA mixes with 0% and 25% RAP have decreased high-temperature properties relative to the HMA mixes with 0% and 25% RAP. Among the WMA mixes, the Evotherm™ mixes (Mixes 3 and 7) have values approximately 4 degrees lower than the Sasobit® or foamed WMA mixes. Surprisingly, the exact opposite trend is seen with 50% RAP mixes; the WMA mixes have increased high-temperature properties relative to the HMA mixes, and the Evotherm™ mix (Mix 11) has a value approximately 4 degrees higher than the Sasobit® and foamed WMA mixes. The trend observed for the 0 and 25% RAP mixes is likely due to reduced binder aging at lower mix aging temperature; however, that does not explain the 50% RAP properties. The more dramatic changes in asphalt properties of the Evotherm™ mixes relative to other WMA mixes seen with 0 and 25% RAP could potentially be explained by the chemistry of the Evotherm™ additive itself, which may have a softening effect on the asphalt, but no specific conclusions can be drawn with the available data.

In general the spread of values of high-temperature properties for a given amount of RAP is 7 degrees or more and would seem to be adequate to reasonably predict the best and worst performing mixes for a given gradation and RAP content. For 0 and 25% RAP, binder data predict that HMA should rut the least and Evotherm™ the most; for 50% RAP Evotherm™ is predicted to rut the least and HMA the most.

Low-temperature binder property values for 0, 25, and 50% RAP WMA mixes with Sasobit® and foam are within about 1 degree of the 0, 25, and 50% RAP HMA mixes, which indicates that the Sasobit® and foam had only a slight effect on low-temperature properties for a given amount of RAP in the mix. The Evotherm™ WMA mixes with 0 and 25% RAP reduced the low-temperature property by approximately 3 degrees relative to the 0 and 25% RAP HMA mixes, indicating that the low-temperature properties are possibly improved relative to the HMA. For the 50% RAP mixes the exact opposite trend is observed for the Evotherm™ mix; the low-temperature property of the Evotherm ™ mixes is almost 8 degrees higher than the HMA mix, indicating that low-temperature properties may be adversely affected.

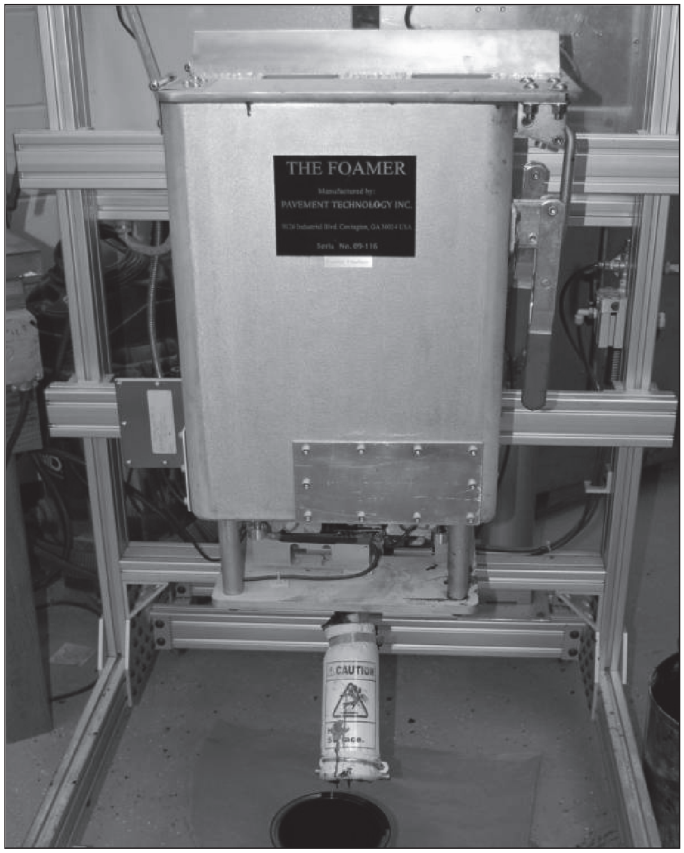
The unusual results for WMA mixes with 50% RAP, especially the Evotherm™ mix, are thought to be at least partly due to difficulty in fully extracting the asphalt from these mixes. Note in Table 6 that all of the asphalt was extracted for the Evotherm™ mix, but not all of the asphalt was successfully extracted for Sasobit® and foam WMA mixes (5.7% asphalt extracted for Mixes 10 and 12, and their design total asphalt contents are 6.1%). The asphalt that could not be extracted is most likely aged asphalt from the RAP; if all of the RAP asphalt had been extracted for the Sasobit® and foam mixes their stiffness would likely be increased. Furthermore, the effects of the solvent extraction and recovery process cannot be fully quantified and may also have contributed to the unusual results observed.

Specimen Preparation

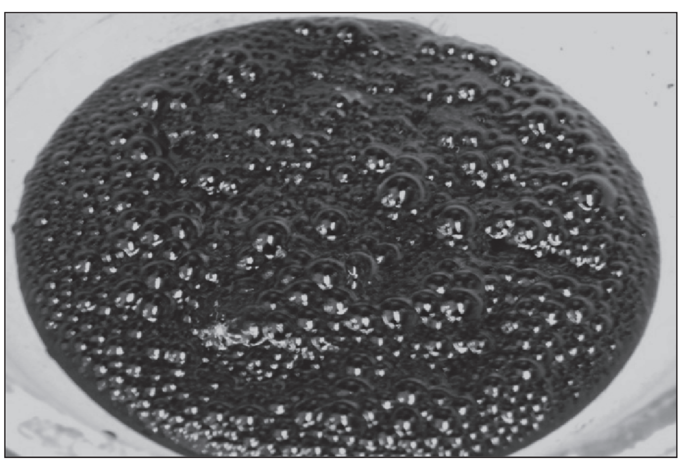
Laboratory Foaming

Foamed asphalt was produced with an initial binder temperature of 163 °C, which reduced to 120 °C during foaming and was added to the heated aggregate at this temperature. The laboratory asphalt foaming device utilized for production of specimens with foamed asphalt is shown in Figure 3*a*. It features an automated control system that automatically proportions the water and asphalt binder at an operator-selected ratio. Figure 3*b* shows a sample of the foamed asphalt (2% water by binder mass).

Figure 3. Laboratory production of foamed asphalt.



a) Laboratory Asphalt Foaming Device



b) Sample of Foamed Asphalt

Mixing and Compaction

For mixtures containing RAP, the RAP was heated for two hours at the same temperature as the virgin aggregate prior to mixing. Virgin aggregate was heated for a minimum of four hours before mixing. Binder was heated to 160 °C before mixing. Mixing was performed with a laboratory bucket mixer. All mixtures were blended, then short-term oven-aged for 2 hours at the compaction temperature before compaction to 75 gyrations with the Superpave gyratory compactor. This compactive effort is recommended for design traffic levels of 0.3 to <3 million equivalent single axle loads (ESALs) by AASHTO R 35 and chosen since no official guidance on selecting design gyrations for airfield mixtures was available.

Sawing of Mixture Beams

For BBR mixture testing, beam specimens were sawn from gyratory compacted specimens of nominal 115 mm height. The first step in preparation of beam specimens from gyratory specimens was to remove two 12.5 mm thick horizontal slices from the top and bottom of the gyratory pill with a masonry saw (Figure 4*a*: Step 1). Four vertical cuts were made on the remaining block followed by a horizontal cut in the middle, such that two square blocks 115 mm on each side with rounded corners were created from the pill (Figure 4*a*: Step 2 and Figure 4*b*).

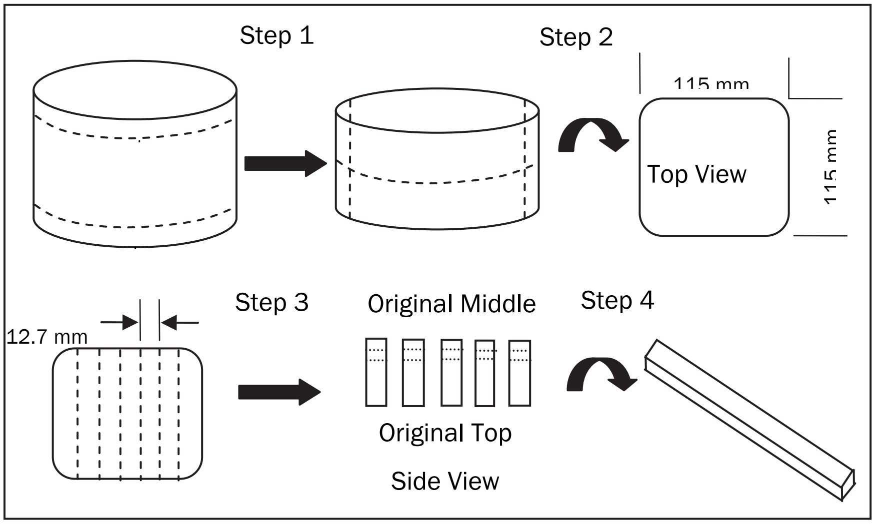
The bottom block was reserved for later testing. Ten mixture beam specimens were sawn from the middle of the top block using a high precision lapidary saw. Six vertical cuts were made in the block (Figure 4*a*: Step 3 and Figure 4*b*) creating five 12.7-mm-wide slices. Two horizontal cuts were made in each of the 12.7-mm-wide slices near what was originally the middle of the gyratory pill (Figure 4*a*: Step 4 and Figure 4*b*) to create two mixture beam specimens from each slice approximately 6-mm thick. A mixture beam specimen before testing of Mixture 1 is shown in Figure 4*c*. When tested in the BBR, the 6-mm dimension was the thickness of the beam.

Test Methods

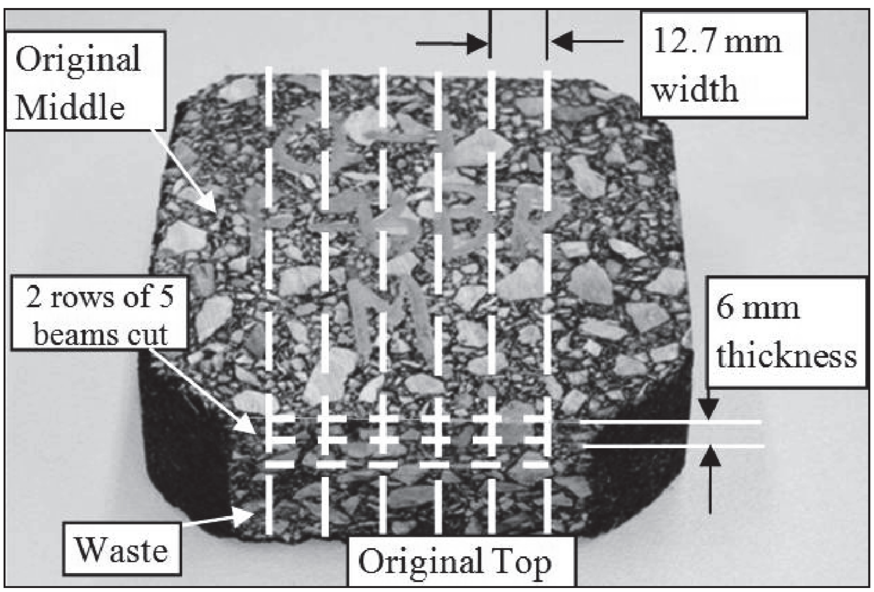
Permanent Deformation

To evaluate permanent deformation resistance, rut testing in the APA was conducted. All APA testing was conducted with a first generation APA according to AASHTO TP 63. The calibration

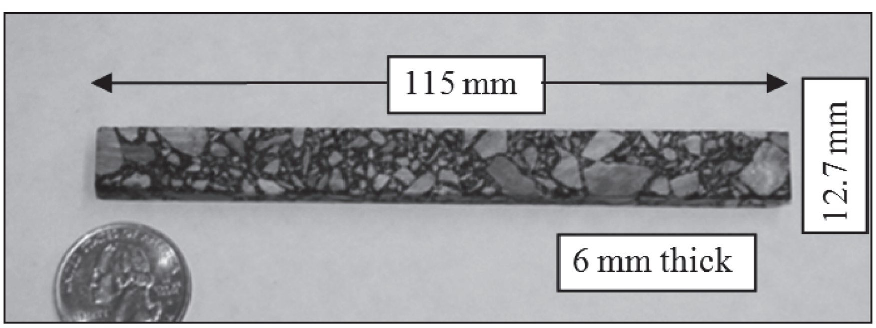
Figure 4. Preparation of mixture beam specimens.



a) Schematic of Preparation Method (Not to Scale)



b) Square Mixture Block Isometric View



c) Final Mixture Beam Specimen (Mixture 1 shown) of the APA was performed once per day before testing began. Automatic measurement of rut depth was used for all data. The test temperature was 64 °C, the wheel load was 445 N, and the hose pressure was 690 kPa. Each test replicate consisted of two mixture specimens under one wheel in the APA. Values were averaged for analysis.

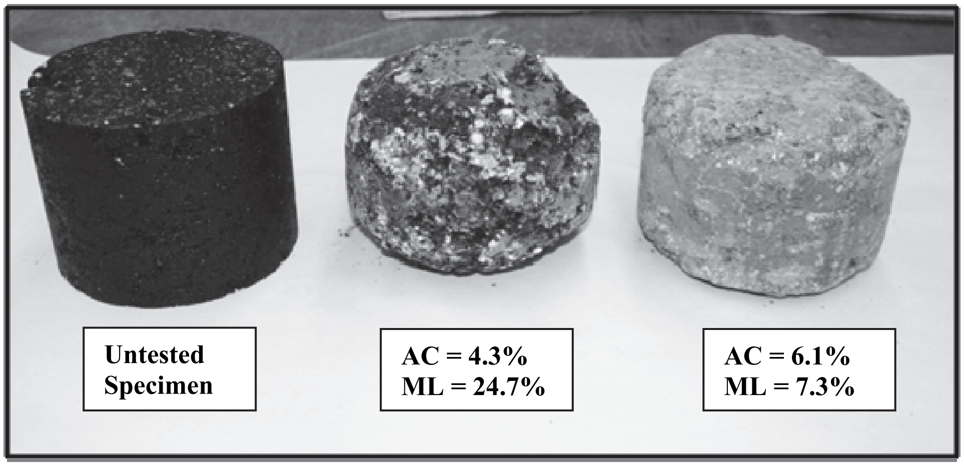
Bulk specific gravity (G_{mb}) of all gravel APA specimens was determined according to AASHTO T 331 (Corelok®), while G_{mb} of all limestone APA specimens was determined according to AASHTO T 166 (traditional SSD method). It was observed during testing that there were differences between void levels measured by the two methods at the desired APA void level. T 331 was observed to result in higher air voids than T 166. The difference was relatively small; Cooley (2003) observed that at 4% air voids there is no difference in the two methods, and at 7% air voids the Corelok® method results in somewhat higher air voids. For the analysis performed in this paper, direct comparison of rutting between limestone and gravel specimens was avoided due to the observed difference in air voids between the methods.

Durability

To evaluate durability of experimental program mixtures, the Cantabro durability test was selected; the test provides a relative measure of the resistance to dry impact and abrasion for a mix. It can be thought of as an indirect measurement of the toughness of a mix. The variability of the Cantabro test for dense-graded mixtures was found to be reasonable for seven surface mixtures tested by Watson et al. (2003), all of which contained 15% RAP or less. For the current experimental investigation, three replicates of each mixture were tested. The durability test was performed on gyratory compacted specimens of nominal 115 mm height, and the test method is described as follows.

Un-aged specimens were dry-conditioned in an environmental chamber at 25 °C a minimum of 12 hours prior to testing. Each specimen was placed in an LA-Abrasion drum without the charge of steel spheres and subjected to 300 revolutions. The loss in mass of the specimen was reported as percent of the original mass; the variable ML is used throughout the rest of this paper to designate durability mass loss. Figure 5 shows tested and un-tested durability specimens with a range of mass loss; the specimens have asphalt contents above and below the design asphalt content.

Figure 5. Durability specimens of mixture 5.

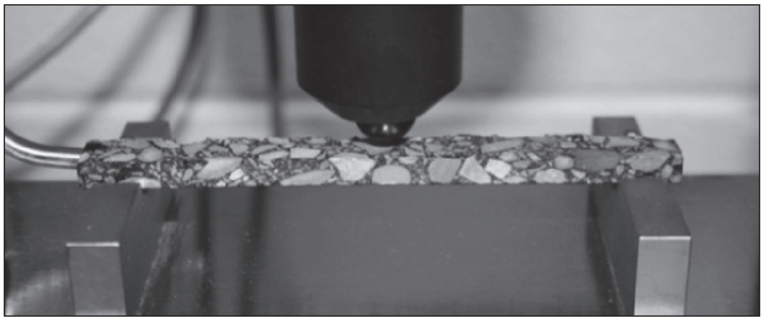


Non-Load Associated Cracking

To evaluate non-load associated cracking, flexural creep testing of mixture beam specimens was conducted in a Bending Beam Rheometer (BBR). Dimensions of the beam specimens were measured and recorded prior to testing. Beam specimens were immersed in the methanol cooling bath of the BBR for 60 ± 5 minutes before testing to ensure they reached thermal equilibrium at the desired test temperature. A CANNON® Thermoelectric BBR was used for testing of all mixture beams. The test parameters were modified from the standard binder test to employ a 4.9 N load and 1,000-second test duration. Specimen deflection at the center of the mixture beam was recorded by the test equipment throughout the test. Figure 6 shows the test fixture with a mixture beam specimen ready for testing after removal from the coolant bath. Deflection data obtained during the BBR test are used to compute two test parameters: 1) mixture stiffness as a function of time; and 2) instantaneous slope of the mixture stiffness curve (m-value). Values of each parameter are calculated at eight discrete loading times over the period of the test. The time points were 8, 15, 30, 60, 120, 240, 480, and 960 seconds.

For each mixture of the experimental program, two gyratory specimens were compacted and mixture beam specimens were prepared from them. For each mixture, two beam replicates were tested from each gyratory specimen at each test temperature. The two test temperatures were -12 °C and -6 °C. A total of eight beam specimens were tested per mixture, four at each test temperature.

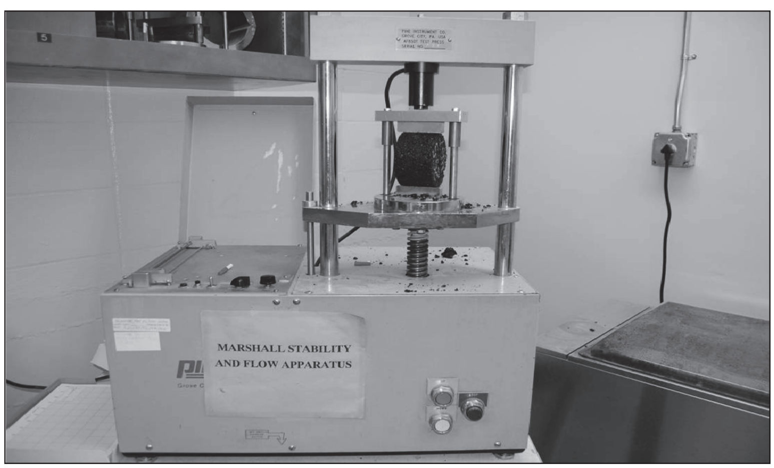
Figure 6. BBR testing of mixture beams.



Moisture Damage

To evaluate moisture damage, ASTM D 4867 was performed on each mixture in the experimental design. A test replicate consisted of six specimens 100 mm in diameter and 63.5 mm thick: three dry and three conditioned. A freeze-thaw cycle was not performed as part of the conditioning process. Air voids of all specimen sets were within the range of the 6% to 8% specified by the test method. Indirect tensile strength testing was conducted using a Marshall stability and flow apparatus shown in Figure 7 to determine the TSR of the mixtures.

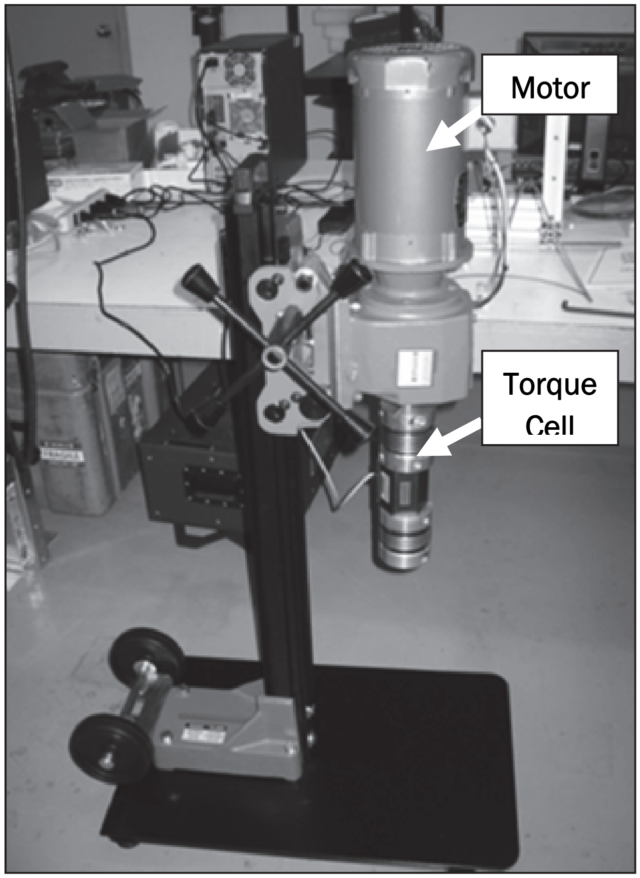
Figure 7. Test apparatus used for moisture damage testing.



Workability

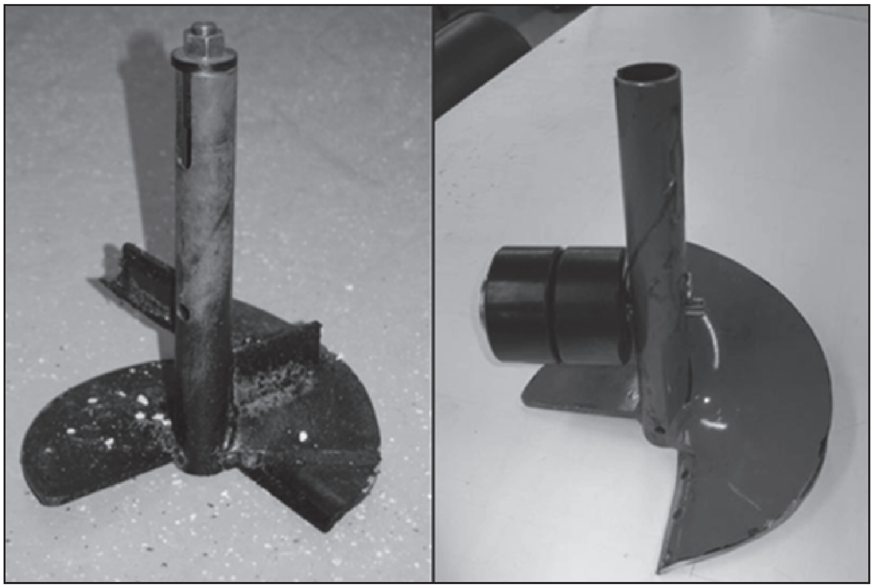
Workability was evaluated using the NCAT Prototype Workability Device shown in Figure 8. This device was manufactured specifically for this project by Instrotek, Inc., in Riley, North Carolina. The method consists of immersing a paddle into a sample of loose asphalt mixture. The device measures the torque required to keep the paddle rotating at a constant speed within the sample. Workability is defined as the inverse of the torque (Gudimettla et al. 2003).

Figure 8. NCAT workability device.



For this project two paddle configurations were evaluated to determine the best configuration that continuously remixed the sample and did not create a shear plane through the mixture, while providing enough mixing to keep a consistent temperature throughout the sample. A shear plane created within the sample would show a consistent workability (torque) over a given temperature range because of a lack of resistance (Gudimettla et al. 2003). The first paddle evaluated shown in Figure 9*a* (Paddle 1) consisted of two arms at different elevations attached to an auger. It was observed that the device stopped several times while testing this paddle, due to aggregate being caught between the arms of the paddle and the container side. The second paddle configuration evaluated shown in Figure 9*b* (Paddle 2) had a roller attached to the shaft to push down the material that the auger normally moves up during the mixing process. This configuration showed good mixing of the material, consistent temperature throughout the sample, and no aggregate breakage was observed. Therefore, testing to evaluate workability of WMA mixtures was performed using the Paddle 2 configuration.

Figure 9. NCAT workability device paddles tested.



a) Paddle 1 b) Paddle 2

For workability testing, an 11 kg sample of mixture was prepared at the standard mixing temperature of 160 °C for HMA or 130 °C for WMA. The bowl and the paddle were also heated to the mixing temperature. The sample was poured into the bowl, with the paddle already inside the bowl, since this paddle configuration did not allow for the opposite procedure of inserting the paddle in the sample mixture. The device was configured to a constant rate of paddle revolution of 15 rpm as recommended by Gudimettla et al. (2003). This rate was considered reasonable to produce a wide range in workability for the temperature range tested.

Mixture temperature was measured using a miniature infrared sensor that came attached to the device. In a small test with limited data, temperature readings from the infrared sensor were compared to a temperature probe that was inserted directly in the mixture when the device was not running. The readings were significantly different from the probe readings. The sensor was moved closer to the sample, and then the temperature readings matched the readings from the temperature probe. Torque and temperature were monitored and recorded continuously at an output rate of 48 data points per second.

Data reduction was performed using regressions between torque and temperature and evaluating standardized residuals for each test. The software Table Curve 2D was used to do the regression analysis. Regressions were of the form given in Equation 1.

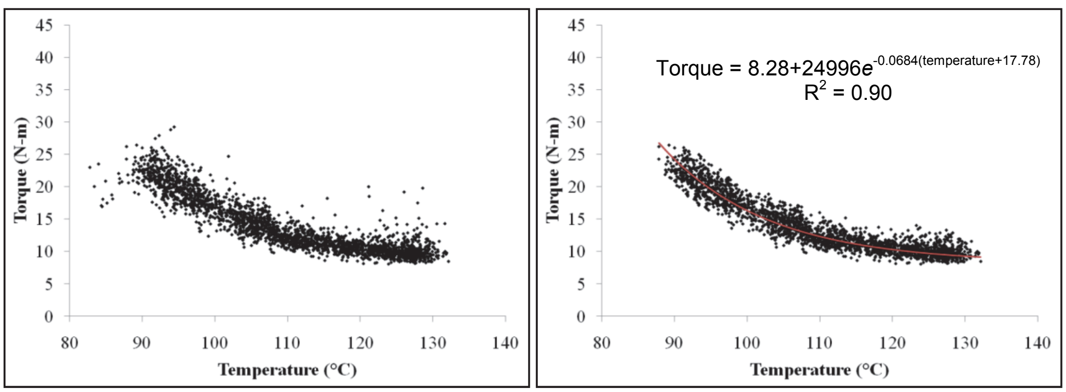
$$Torque = a + be^{-c(temperature+17.78)} \qquad (1)$$

where:

Torque	=	torque required to rotate the paddle, N-m
Temperature	=	mixture temperature, °C
a, b, c	=	regression constants

Figure 10 shows an example of the typical raw data from the workability device and the final data and regression model without outliers. Once the data from each test were reduced, the final regression models were used to compare the workability of the different mixtures.

Figure 10. Typical data reduction from workability test.



a) Typical raw data b) Typical data with outliers removed

4 Experimental Results and Analysis

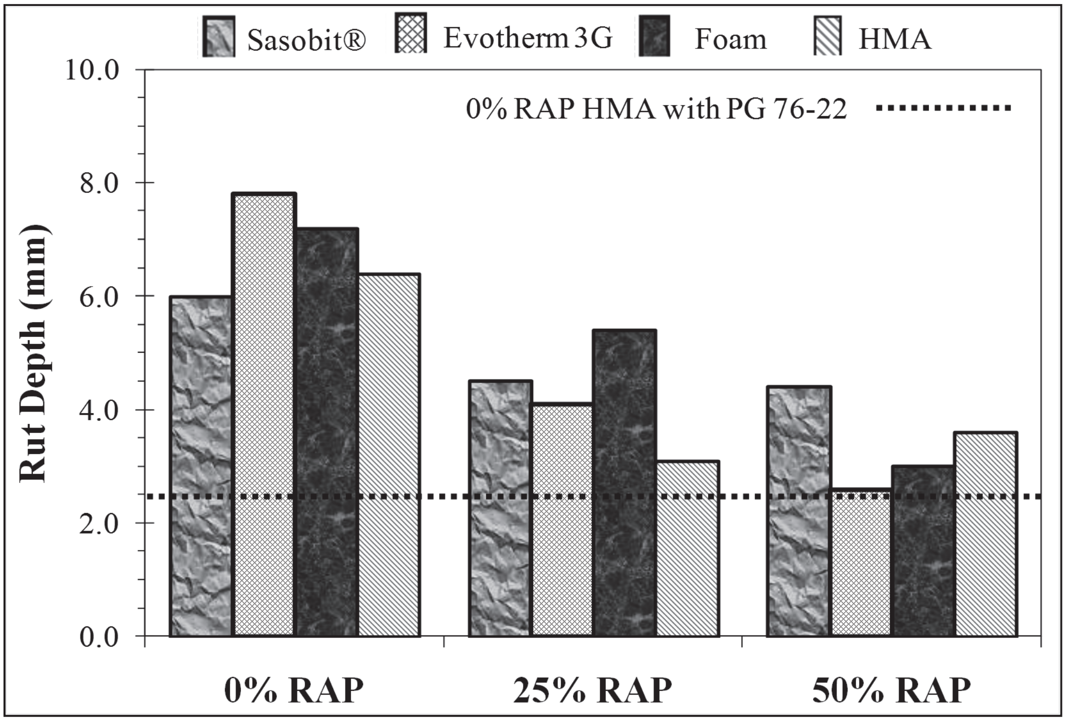
Results from the experimental evaluation, organized by performance test, are presented in this chapter. Data are grouped by aggregate type and RAP content to allow comparison of WMA mixtures to HMA mixtures. Statistical analyses of the data were conducted as appropriate and results are discussed as well.

Permanent Deformation

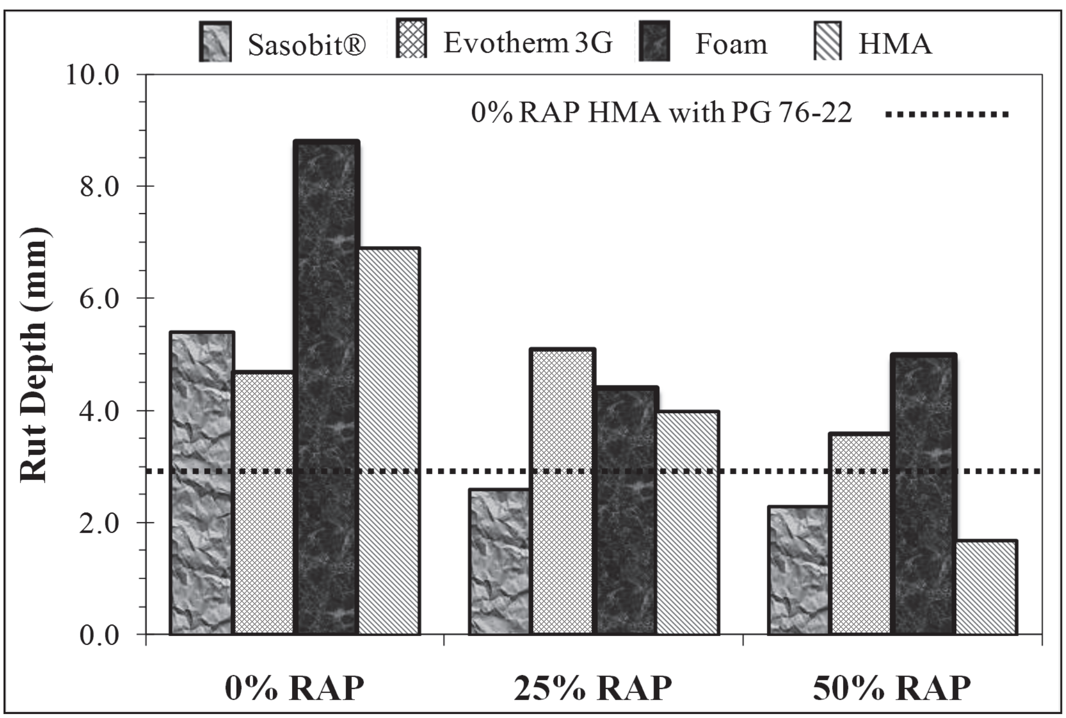
Figure 11 provides rut-depth test results for all 24 mixtures; the raw data can be found in Tables A-1 and A-2. An 8-mm pass/fail criterion has been suggested for the test conditions employed by Brown et al. (2001), and this value was used herein. All limestone mixtures rutted less than 8 mm, indicating they should perform adequately with regard to rutting. All gravel mixes with exception of the 0% RAP foam rutted less than 8 mm; the foam specimen rutted 8.8 mm, which does not greatly exceed the pass/fail criteria. One possible explanation for the rutting behavior of the 0% RAP foamed gravel is that the design effective asphalt content is 5.7%, while the other two 0% RAP WMA mixes produced at the same temperature have an effective asphalt content of 5.4%. It must be kept in mind that the standard APA test conditions used for this testing were developed to represent the loading conditions present in highways and may not necessarily be representative of airfield loading conditions.

PG 76-22 (modified with radial SBS polymer) binder was used in place of PG 67-22 binder for Mixtures 1 and 13 (0% RAP HMA controls) to provide a reference for comparison to the effects from inclusion of RAP. A 0% RAP aggregate with a polymer-modified binder is considered a premium mixture that would be relatively expensive and is a good reference to compare with other mixtures. The primary purpose of using polymer-modified binder is for rutting resistance. This reference using a mixture with modified asphalt is provided in Figure 11 with a horizontal line. The data generally showed that the mixtures being evaluated had higher rutting than the modified asphalt mixture used for comparison. Generally there is less rutting as the amount of RAP increased. At 50% RAP, the amount of rutting is comparable to that for the control-modified asphalt mixture.

Figure 11. Rutting test results.



a) Rutting data for limestone mixes (1 to 12)



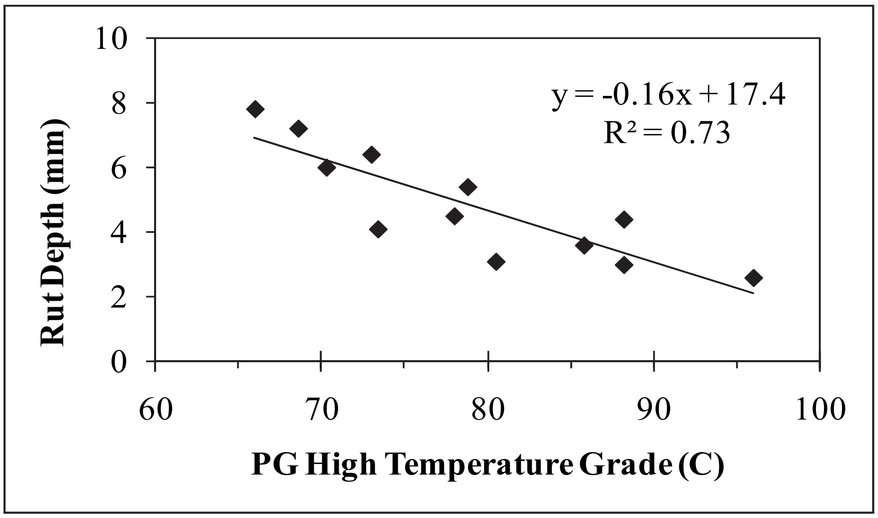
b) Rutting data for gravel mixes (13 to 24)

Differences in rutting for particular gradations are generally quite small; but some overall observations can be made for WMA compared to HMA. Foam mixes rutted more than HMA with the same gradation in 5 of

6 cases. Sasobit® rutted less than HMA in 3 of 6 cases, including both 0% RAP cases. Evotherm™ rutted more than HMA in 4 of 6 cases.

The binder data provided in Table 6 were used to determine if a correlation existed with limestone specimen rut data. Binder data suggest that HMA and Sasobit® mixtures should rut less with 0% RAP than Evotherm™ 3G and foam, which they did. Figure 12 plots the PG high-temperature grade of mixes from Table 6 versus total rut depth. This correlation clearly shows that the resulting recovered binder grade had a reasonably high correlation ($R^2 = 0.73$) with the amount of rutting in the APA.

Figure 12. Correlation of PG high-temperature grade to rut depth.



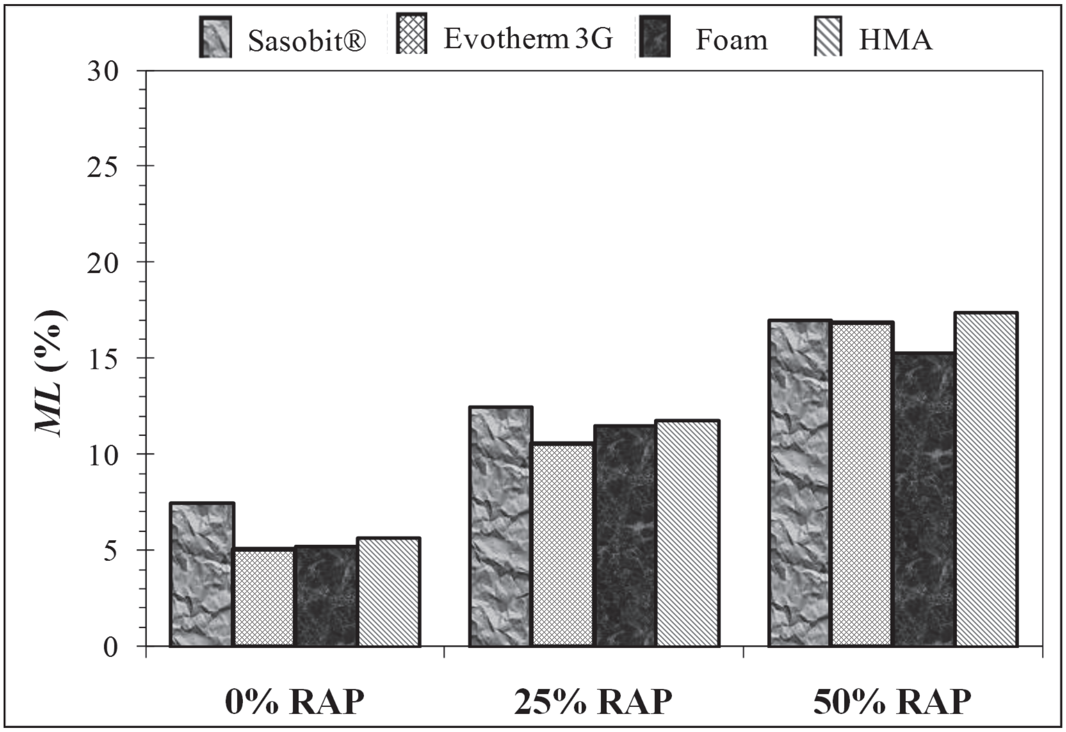
The binder data presented in Table 6 correctly predicted which mixture would rut the least for a given amount of RAP in the mixture in three of the six possible cases (only the three limestone mixes were correctly predicted). It only correctly predicted which mixture would rut the most for a given amount of RAP in the mixture in one of the six possible cases (gravel mixture with 25% RAP). These results indicate that, while the high-temperature binder property was able to discern general trends in rutting performance as the amount of RAP is increased, it was a relatively poor predictor of specific best- or worst-performing mixes for a given level of RAP. This is evidence of the problems that can be associated with using only binder data to study mixtures with high RAP contents.

Durability

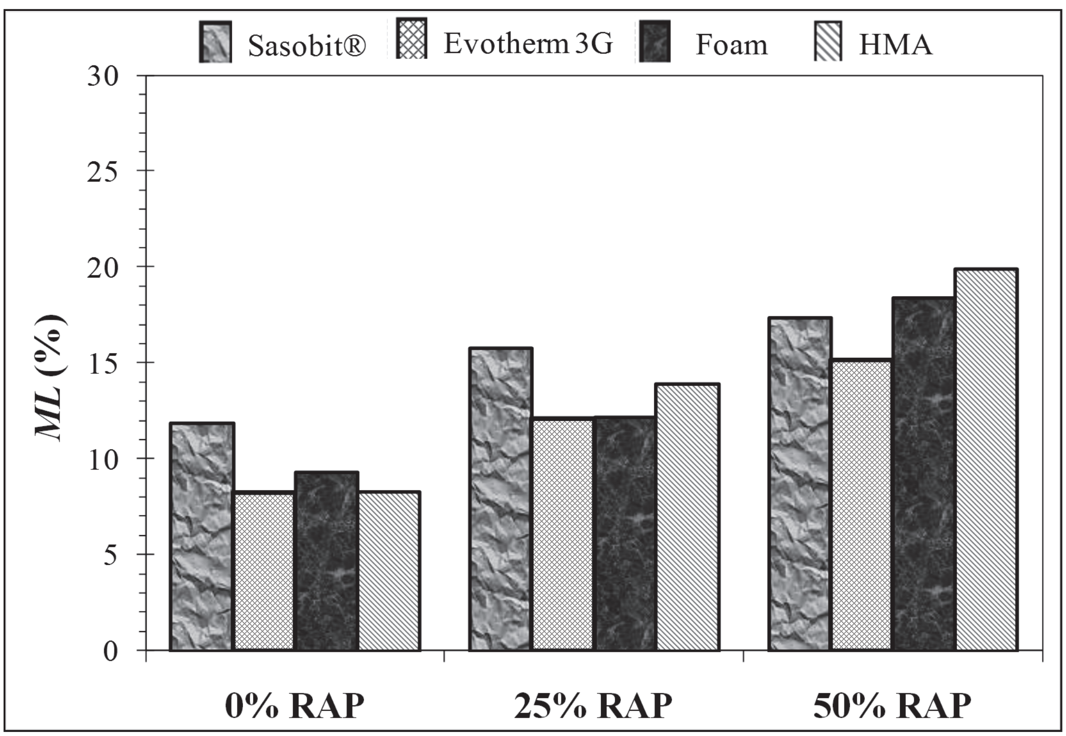
Results of durability testing for the 24 mixes are presented in Figure 13; the raw data can be found in Tables A-3 to A-4. Analysis of variance (ANOVA) testing was performed at the 5% significance level, assuming that the data were normally distributed. Results indicated that within each gradation no statistically significant differences were found between the hot-mix control and the three warm-mix technologies or between the warm-mix technologies. However, visual observation of the data for 0% and 25% RAP indicates that Sasobit® mixes tended to have higher mass loss (i.e., decreased durability) than any other mixes. This aligns with the results reported by (SasolWax 2004; Mallick et al. 2008) that Sasobit® can have a stiffening effect at temperatures below its melting point. The effect of RAP addition to the mixes is apparent; the mass loss is increased as additional RAP is incorporated into the mixes. Gravel mixes had higher mass loss than limestone mixes in 11 of 12 cases (92% of the time). This is an unusual result since gravel aggregate mixtures typically had higher total and effective binder contents than limestone aggregate mixtures; additional research would be required to investigate this issue.

To better interpret the effects of RAP on durability, statistical comparisons were made using the Tukey multiple comparison procedure; the results are summarized in Table 7. Gradations with the same Tukey letter grouping are not significantly different from each other; all gradations in a letter grouping are significantly different than those in other letter groupings. For the limestone gradations the 0% RAP, 25% RAP, and 50% RAP gradations are all three significantly different from one another. The same trend held true for the gravel gradations. The limestone and gravel 0% RAP gradations (LS-1 and GR-1) were significantly different from one another; this implies that in the absence of RAP, virgin aggregate type has a significant effect on durability results. However the limestone and gravel 25% RAP gradations (LS-2 and GR-2) were not significantly different from one another. The limestone and gravel 50% RAP gradations (LS-3 and GR-3) were also not significantly different from one another. Based on the data, the presence of 25% and 50% RAP in the mixture appears to overwhelm effects due to virgin aggregate type. As the gradations are all quite similar, it is likely that the contribution of RAP asphalt to the recycled mixes is the dominating factor leading to this result. While this test has not been proven to be related to durability in the field, it is believed that it is a good test for ranking the mixtures. Further research is needed to investigate a relationship between laboratory results and field performance. Results of test sections containing 45% RAP at the NCAT test track led West et al. (2009) to observe that high RAP mixes would likely have good raveling resistance.

Figure 13. Durability test results.



a) Durability data for limestone mixes (1 to 12)



b) Durability data for gravel mixes (13 to 24)

Table 7. Tukey multiple comparison test of mass loss.

Gradation Number	Mean Mass Loss (%)	Tukey Grouping			
LS-1	5.8	A			
LS-2	11.6			C	
LS-3	16.7				D
GR-1	9.4		B		
GR-2	13.5			C	
GR-3	17.7				D

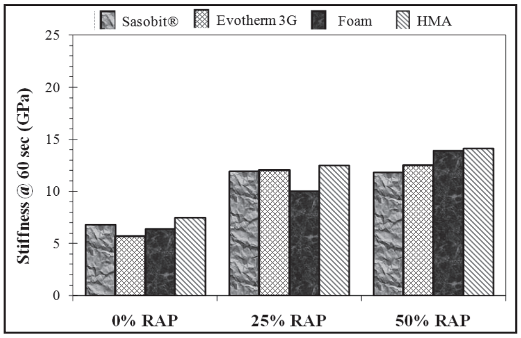
Note: Experimental treatments with the same letter grouping are not statistically significantly different at the 5% significance level.

Non-Load Associated Cracking

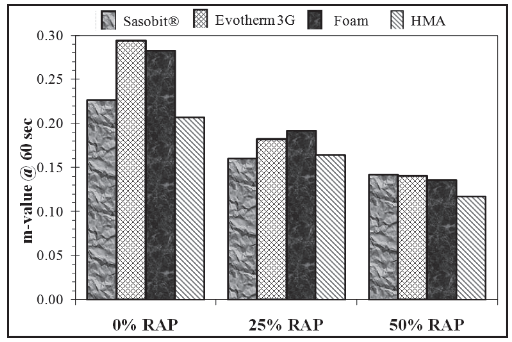
Figures 14 and 15 present mixture stiffness and m-value (slope of stiffness curve) results at 60 seconds when tested at -6 °C and -12 °C, respectively. The raw data can be found in Tables A-5 to A-10. Analysis of variance (ANOVA) testing was performed at the 5% significance level assuming that the data was normally distributed. Mixture stiffness data from each test temperature were considered separately. Within each gradation, no statistically significant differences were found between the hot-mix control and the three warm-mix technologies or between the warm-mix technologies at either test temperature. However, when RAP was included as part of the mixture, in nearly all cases at both test temperatures the warm-mix technologies were less stiff than the hot mix. It is thought that this is likely due to the decreased amount of aging of the binder when mixing using the WMA temperatures. Similar trends are seen in the m-value data but with m-value decreasing as RAP content increases. Differences in m-value between RAP contents are slightly more pronounced for -6 °C data than for -12°C data. In general, increased stiffness and decreased m-value for high RAP mixes indicate that these mixes are likely more brittle than the 0% RAP mixes and consequently may have higher potential for low-temperature cracking.

The effect of RAP on low-temperature stiffness values was found to be statistically significant by ANOVA testing. To better interpret the data, two Tukey multiple comparison tests were performed, one for each test temperature; all results are given in Table 8. For a specific temperature, gradations with the same Tukey letter grouping are not significantly different from each other; all gradations in a letter grouping are significantly different from those in other letter groupings. For both test temperatures the two 0% RAP gradations are not significantly different, indicating that in

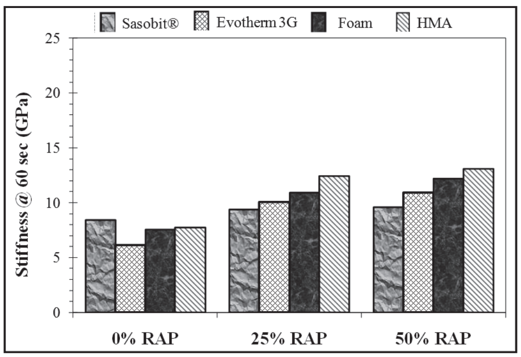
Figure 14. Mixture stiffness and m-value at 60 seconds tested at -6 °C.



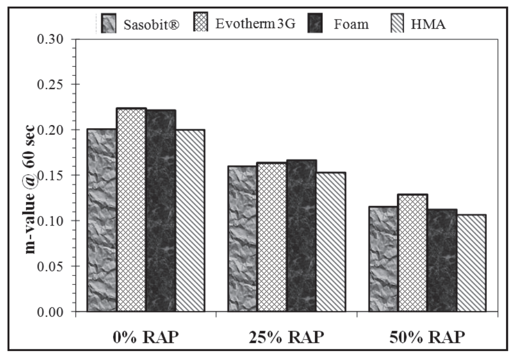
a) Stiffness for limestone mixes (1 to 12)



b) M-value for limestone mixes (1 to 12)

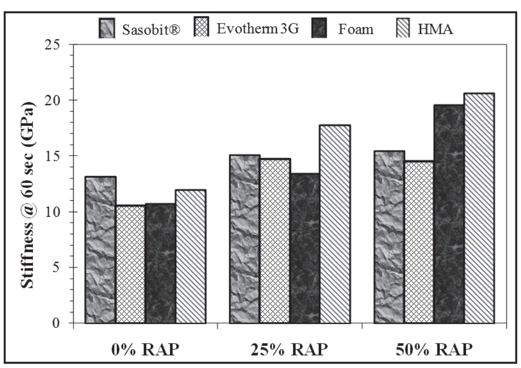


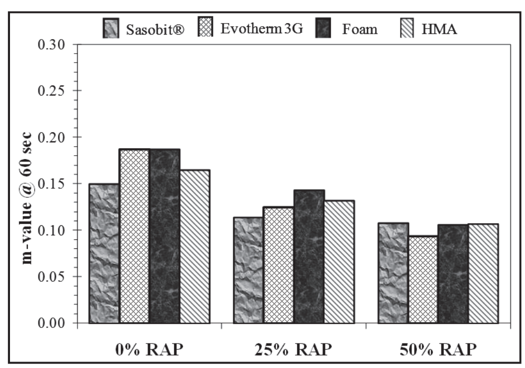
c) Stiffness for gravel mixes (13 to 24)



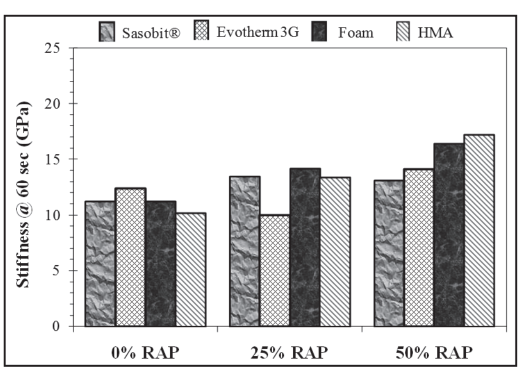
d) M-value for gravel mixes (13 to 24)

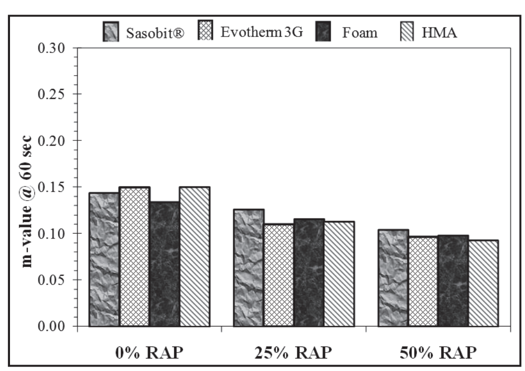
Figure 15. Mixture stiffness and m-value at 60 sec tested at -12 °C.





a) Stiffness for limestone mixes (1 to 12)b) M-value for limestone mixes (1 to 12)





c) Stiffness for gravel mixes (13 to 24) d) M-value for gravel mixes (13 to 24)

Table 8. Tukey multiple comparison tests of mixture stiffness at 60 seconds.

Test Temperature	Gradation Number	Mean Stiffness (GPa)	Tukey Grouping		
-6 C	LS-1	6.6	A		
	LS-2	11.6		B	C
	LS-3	13.1			C
	GR-1	7.5	A		
	GR-2	10.7		B	
	GR-3	11.4		B	C
-12 C	LS-1	11.6	D		
	LS-2	15.2		E	F
	LS-3	17.5			F
	GR-1	11.2	D		
	GR-2	12.8	D	E	
	GR-3	15.2		E	F

Note: Experimental treatments with the same letter grouping are not statistically significantly different at the 5% significance level.

the absence of RAP, virgin aggregate type did not appear to affect mixture stiffness. When RAP is included in the mixtures, the results are chained together and no specific conclusions can be drawn; the only significant differences (at either test temperature) are between LS-2 and GR-3. Based on the results, the increase in mixture stiffness from 0% to 25% RAP is generally significant; however, the subsequent increase in stiffness from 25% to 50% RAP is generally not significant or as large. This is in contrast to the results reported by Li et al. (2008), who found little difference between 0% and 20% RAP mixtures but a large reduction in low-temperature fracture resistance for 40% RAP mixtures.

Tukey multiple comparison tests were likewise performed for m-value data at each test temperature; results are given in Table 9. For -6 °C data, results are chained together, but 50% RAP mixes have significantly lower m-values than 0% RAP mixes. For -12 °C data, the LS-1 gradation has significantly higher m-value than the other gradations.

For the limestone mixtures, correlations between mixture stiffness and low-temperature binder grade (from Table 6) were generally poor as shown in Figure 16*a*, although the -6 °C test data were slightly better than the -12 °C test data. Correlations between mixture stiffness and binder stiffness at -12 °C test temperature were also generally poor (Figure 16*b*). This result is aligned with the evidence presented by Huang et al. (2005) for limited mechanical blending of RAP asphalt and virgin binder.

Table 9. Tukey multiple comparison tests of mixture m-value at 60 seconds.

Test Temperature	Gradation Number	m-value	Tukey Grouping			
-6 C	LS-1	0.253	A			
	LS-2	0.175	A		C	
	LS-3	0.134			C	D
	GR-1	0.212	A	B		
	GR-2	0.161		B	C	D
	GR-3	0.116				D
-12 C	LS-1	0.172	E			
	LS-2	0.128		F		
	LS-3	0.104			G	
	GR-1	0.144		F		
	GR-2	0.116		F	G	
	GR-3	0.098			G	

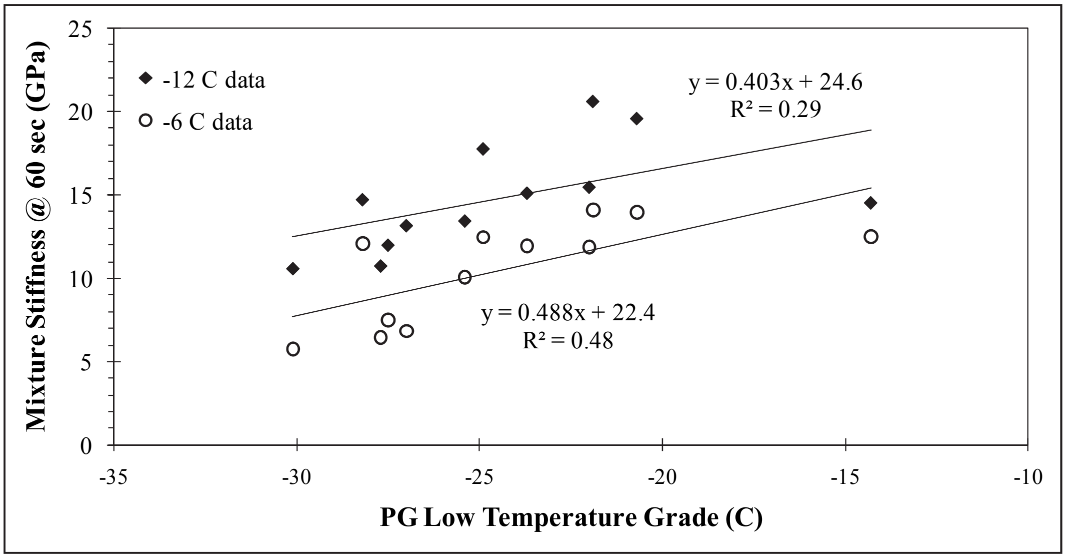
Note: Experimental treatments with the same letter grouping are not statistically significantly different at the 5% significance level.

In addition, the binder data provided in Table 6 would seem to indicate that the 50% RAP Evotherm™ mixes would be much stiffer than the other 50% RAP mixes; this is not the case for the mixture data presented in Figures 14 and 15. These poor correlations of mixture properties and binder properties provide evidence of the problems that can be associated with using only binder data to study mixtures with high RAP contents.

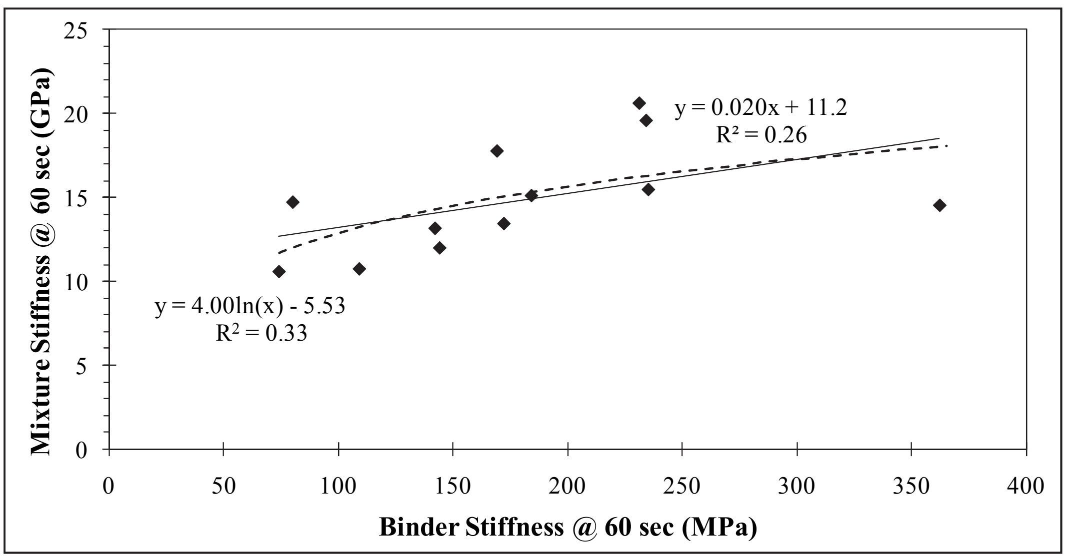
Moisture Damage

Figures 17 to 19 present dry and wet tensile strengths and TSR results for 0, 25, and 50% RAP mixes, respectively. Data are organized by aggregate type and production temperature. The thick horizontal line on all figures represents the pass/fail specification TSR value of 0.75. Raw data can be found in Tables A-11 and A-12. The production temperatures are described in the discussion as: low temperature (130/116 °C), intermediate temperature (146/132 °C), and high temperature (160/146 °C). Temperatures in parentheses are mixing temperature followed by compaction temperature.

Figure 16. Correlations of low-temperature mixture stiffness.



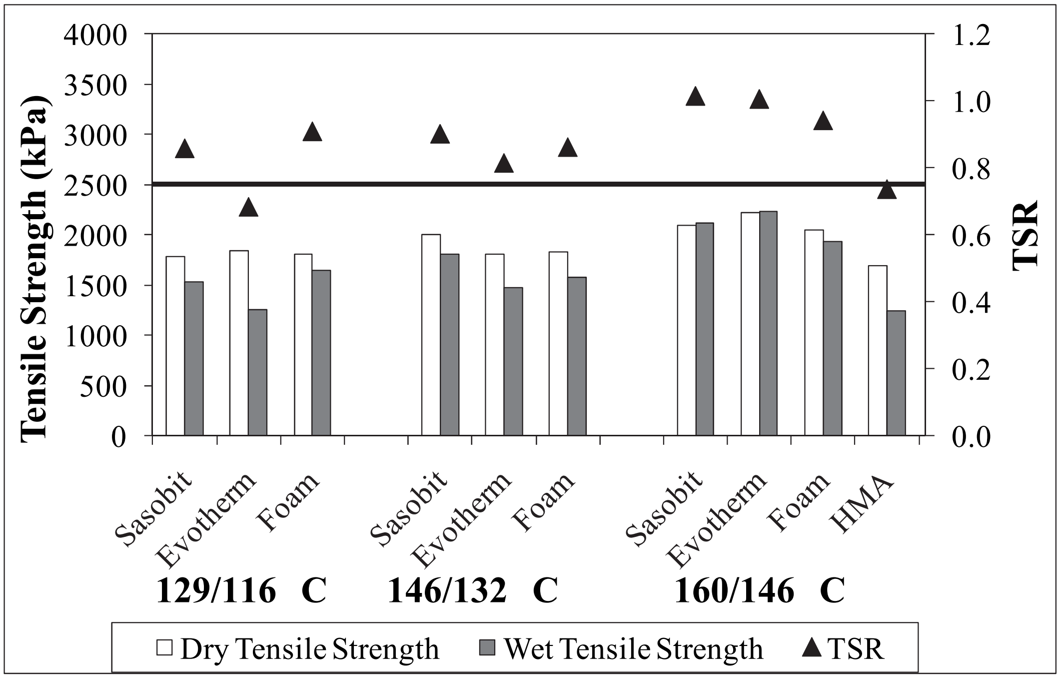
a) Correlation of mixture stiffness to PG low-temperature grade



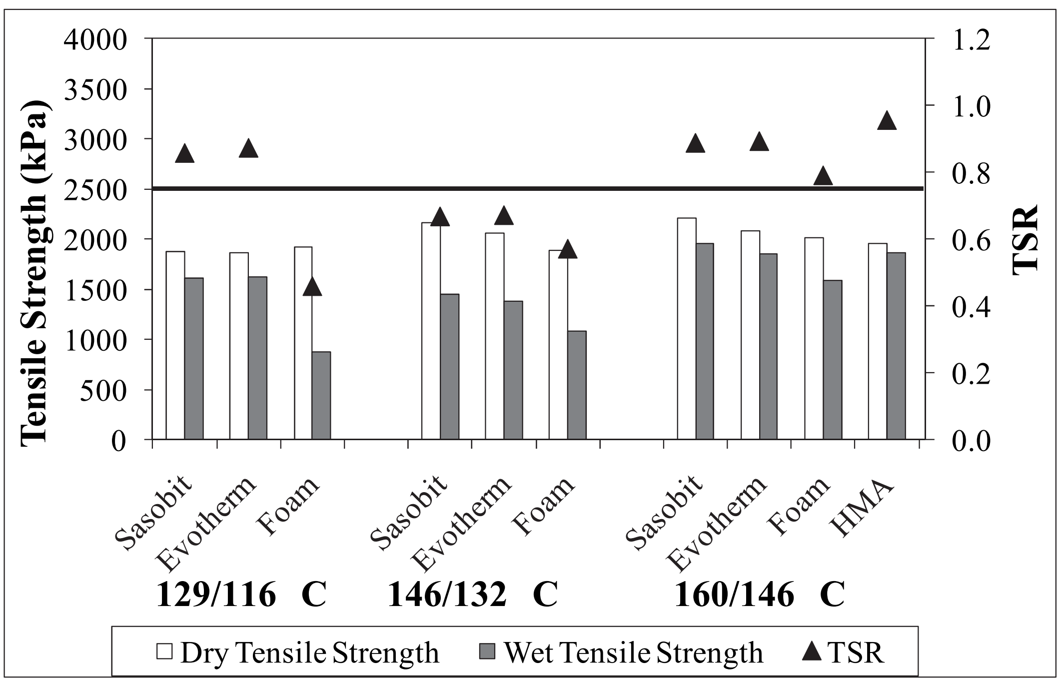
b) Correlation of mixture stiffness to binder stiffness (-12 °C data)

Figure 17 presents results for limestone and gravel mixes without RAP. HMA mixes are presented only at the high temperature. WMA mixes had dry tensile strengths equal (within the test precision) or stronger than HMA for both aggregates at all production temperatures. All three WMA technologies improved the wet tensile strength of the limestone mixes at all temperatures, compared to the limestone HMA mix. For the gravel mixes, the wet tensile strength was reduced when WMA technologies were used, except at high temperature.

Figure 17. Moisture damage results for 0% RAP mixtures by production temperatures.

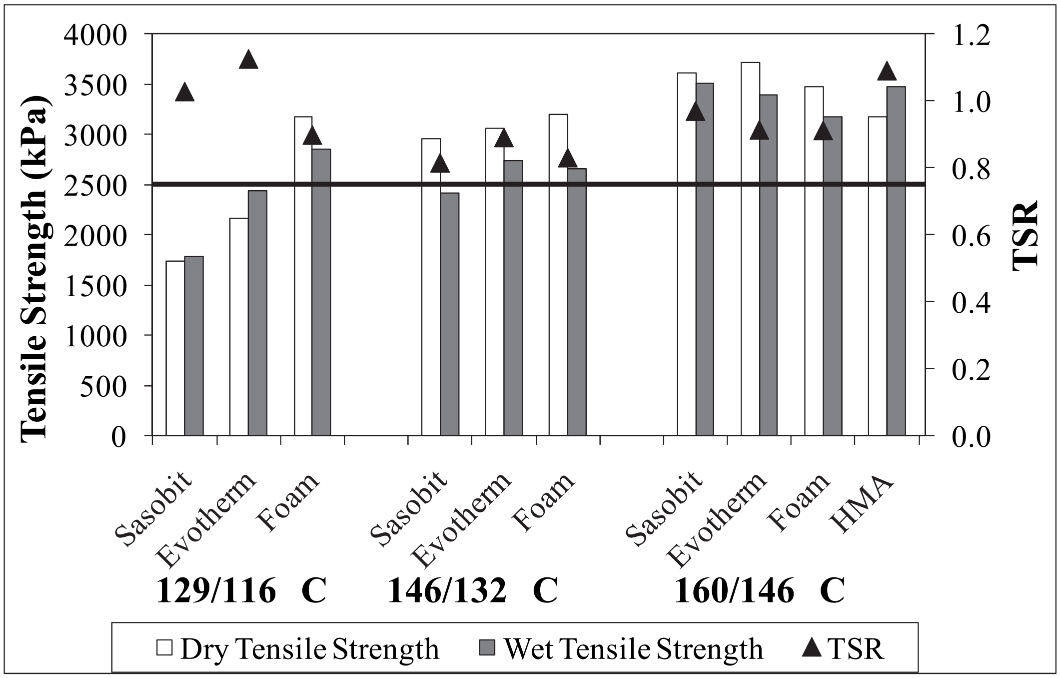


a) TSR data for limestone mixes (1 to 4)

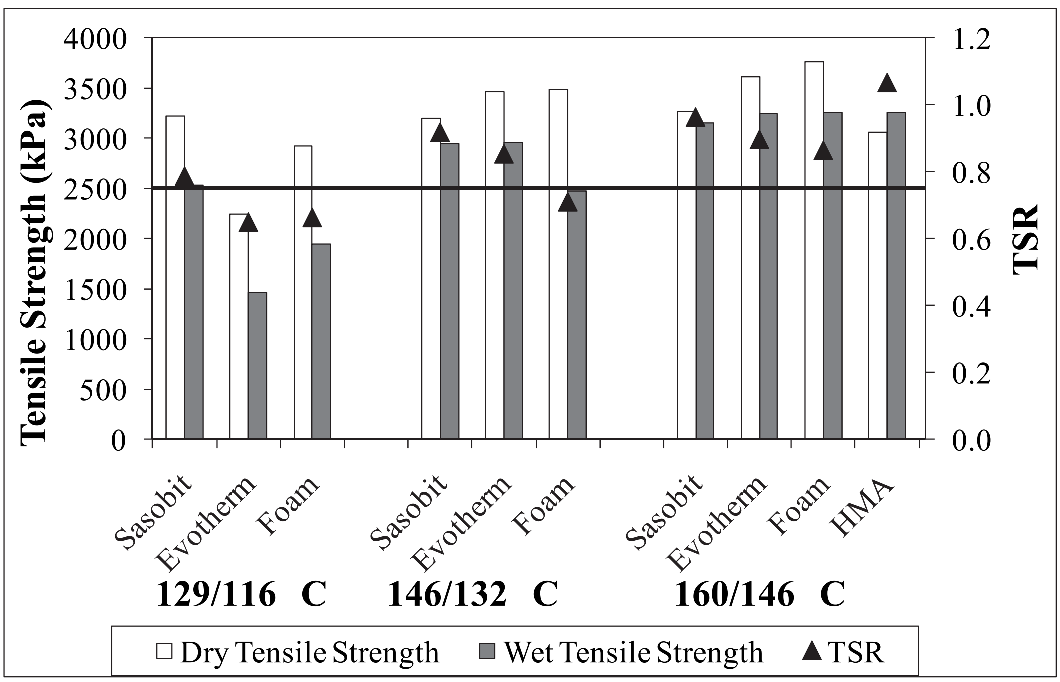


b) TSR data for gravel mixes (13 to 16)

Figure 18. Moisture damage results for 25% RAP mixtures by production temperatures.

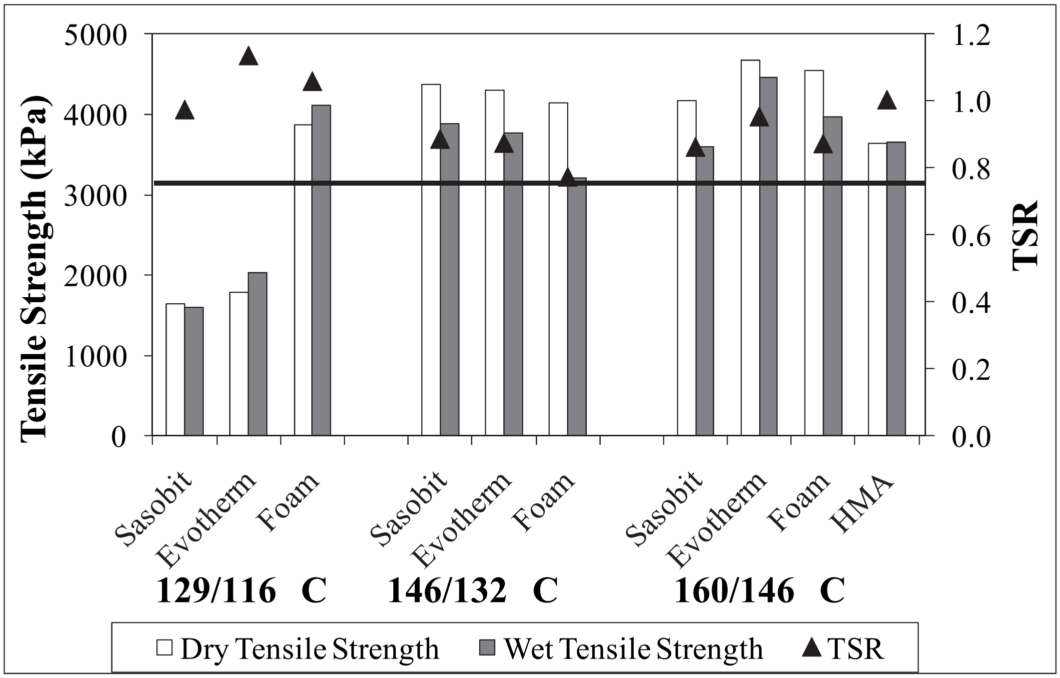


a) TSR data for limestone mixes (5 to 8)

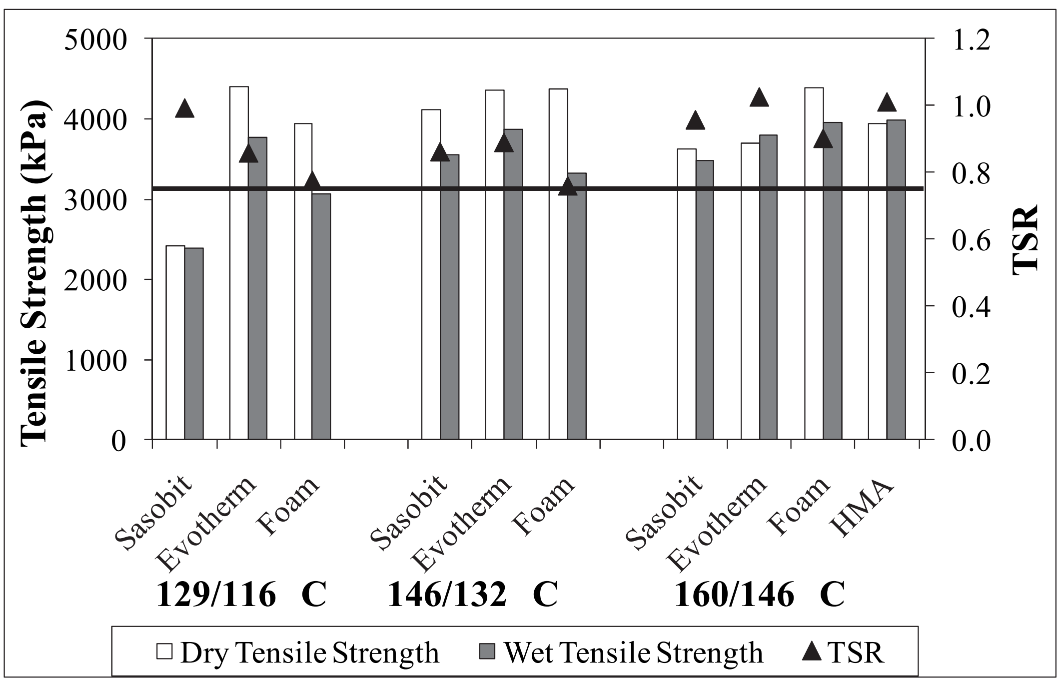


b) TSR data for gravel mixes (17 to 20)

Figure 19. Moisture damage results for 50% RAP mixtures by production temperatures.



a) TSR data for limestone mixes (9 to 12)



b) TSR data for gravel mixes (21 to 24)

Increasing production temperature generally increased TSR values for most of the mixes. Performance of the HMA limestone mix (TSR = 74) did not quite meet the TSR specification. However, when WMA technologies were used with limestone aggregate, TSR values generally improved and were acceptable, except for the Evotherm™ mix at the low temperature (TSR =

0.64). Of the gravel mixes, only 5 of 9 WMA cases met TSR requirements. One interesting observation was that TSR values for Evotherm™ and Sasobit® gravel mixes decreased to a level below the requirement when the production temperature was increased from low to intermediate. However, these values improved and met the requirements at the high temperature. This could be due simply to test variability, but it was not investigated further due to laboratory time constraints. Visible stripping occurred in some cases such as the virgin gravel mix with foamed asphalt when mixed at low temperature as shown in Figure 20 (TSR = 0.46). This was also the lowest TSR value of all mixes. However, TSR values of foamed gravel increased noticeably with production temperature.

Figure 20. Visible aggregate stripping on conditioned mixture 16 specimens.

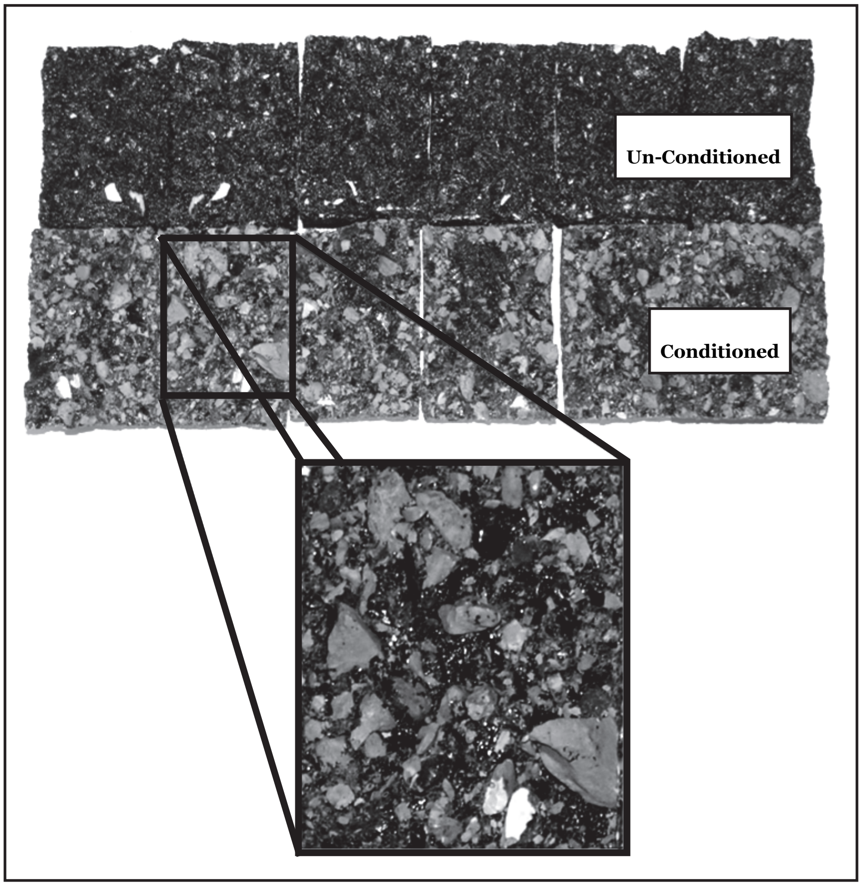


Figure 18 presents moisture damage results for limestone and gravel mixes with 25% RAP. Generally, the performance of all mixes improved when 25% RAP was used compared to the performance of mixes without RAP (Figure 17); all the limestone mixes and 6 of 9 gravel WMA mixes met the TSR criteria. This improvement in resistance to moisture damage was even more noticeable when 50% RAP was used (Figure 19), as all the mixes had adequate TSR values. In most cases, relatively large increases in the tensile strengths of WMA mixes occurred as RAP contents increased. All limestone mixes with 25 and 50% RAP content performed acceptably when mixed at the three different temperatures. All 50% RAP gravel mixes had acceptable TSR values at the three production temperatures. The best example of improved TSR values by increasing RAP content is for the foamed gravel and the low production temperature, where TSR went from 0.46 to 0.66 to 0.78 as RAP content increased from 0% to 25% to 50%.

Workability

Figures 21 to 23 present averaged workability data for limestone mixtures organized by RAP content. The raw data can be found in Figures A-1 to A-3 and Table A-13. For mixes without RAP (Figure 21), torque values for WMA mixes are lower than HMA mixes for a given temperature, potentially indicating better workability. Torque values for the WMA mixes at about 120 °C are similar to torque values for the HMA mix at its normal compact-tion temperature of 146 °C. Little difference is seen between WMA mixes except at the lowest temperatures. Curves for each mix increase only slightly with decreasing temperature down to about 110 °C. Below this point the curves begin to increase noticeably, potentially indicating decreased workability. These results are promising for workability of WMA mixes, but it is not clear what they mean in terms of behavior during construction.

WMA mixes containing 25% RAP (Figure 22) also require less torque than the corresponding HMA mix at the same temperature. Again, little difference in WMA mixes is observed except at the lowest temperatures. Torque for the 25% RAP HMA at its normal compaction temperature is nearly the same as for the 0% RAP HMA (≈ 10 N-m), but torque values for the 25% RAP mixes increase at a faster rate with decreasing temperature than for the 0% RAP mixes.

The torque curve for HMA with 50% RAP (Figure 23) starts higher than the 0 and 25% RAP HMAs at their normal compaction temperature and increases steeply. However, the final torque value at 90°C is not any higher than the 25% RAP HMA. Torque curves for WMA mixes with 50% RAP behave similarly to those for 25% RAP WMA mixes. Once again, WMA mixes appear to be more workable than HMA but cannot be differentiated from each other.

Figure 21. Workability data for 0% RAP limestone mixtures.

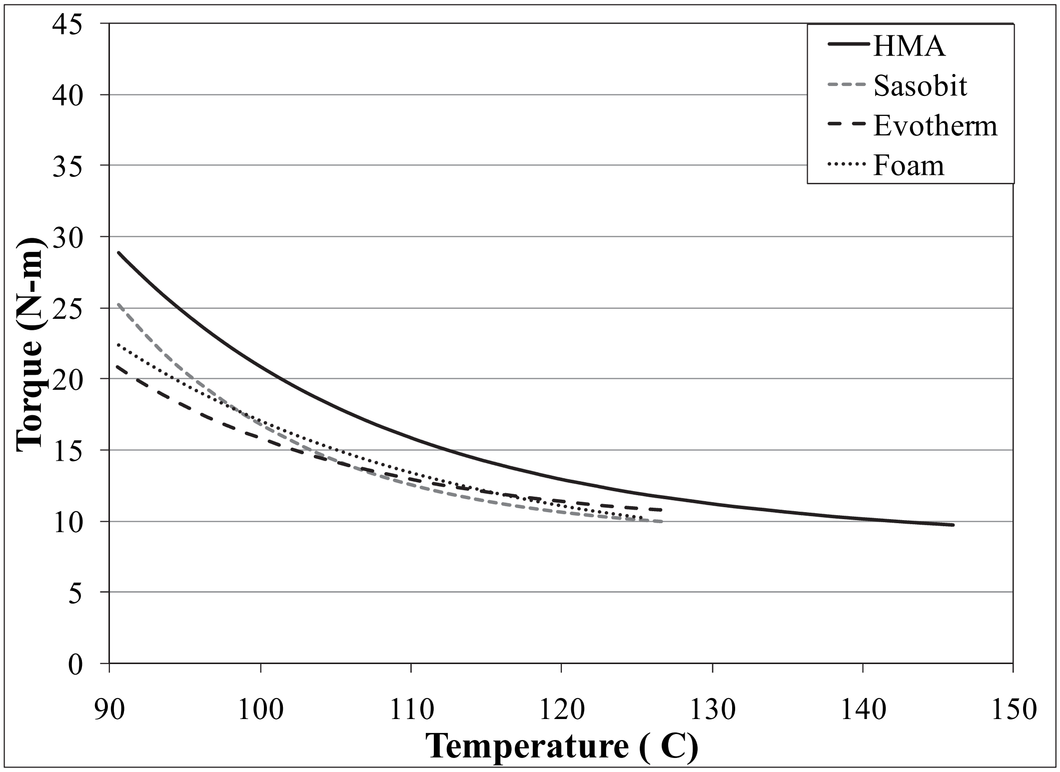


Figure 22. Workability data for 25% RAP limestone mixtures.

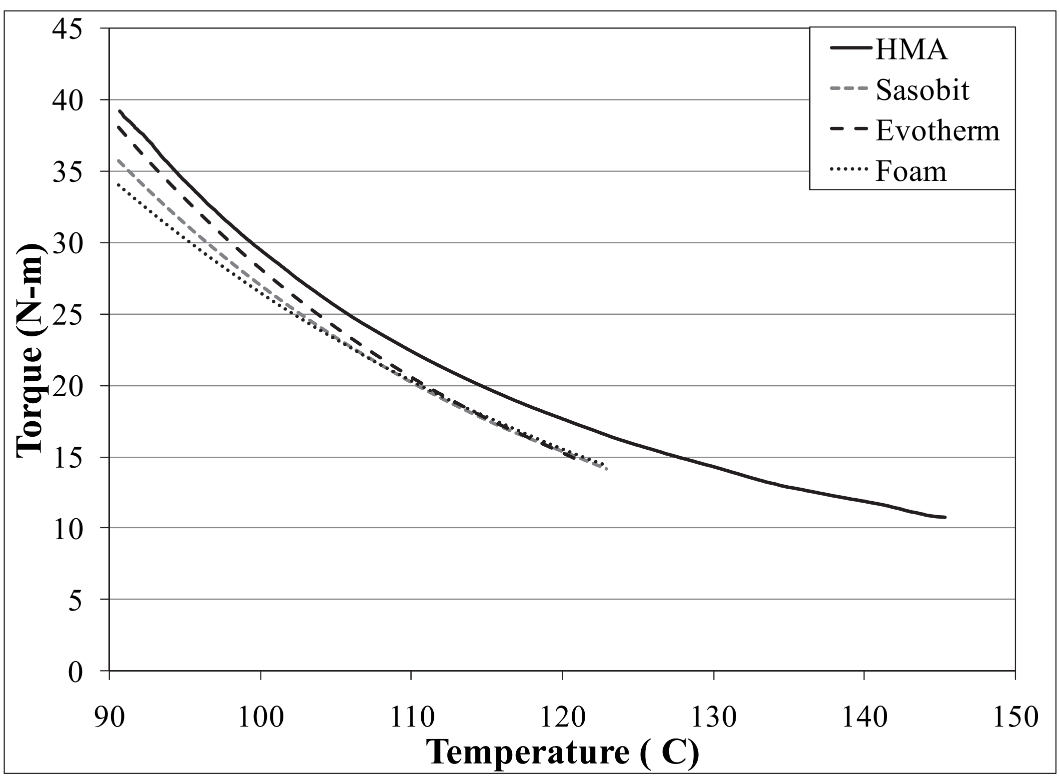
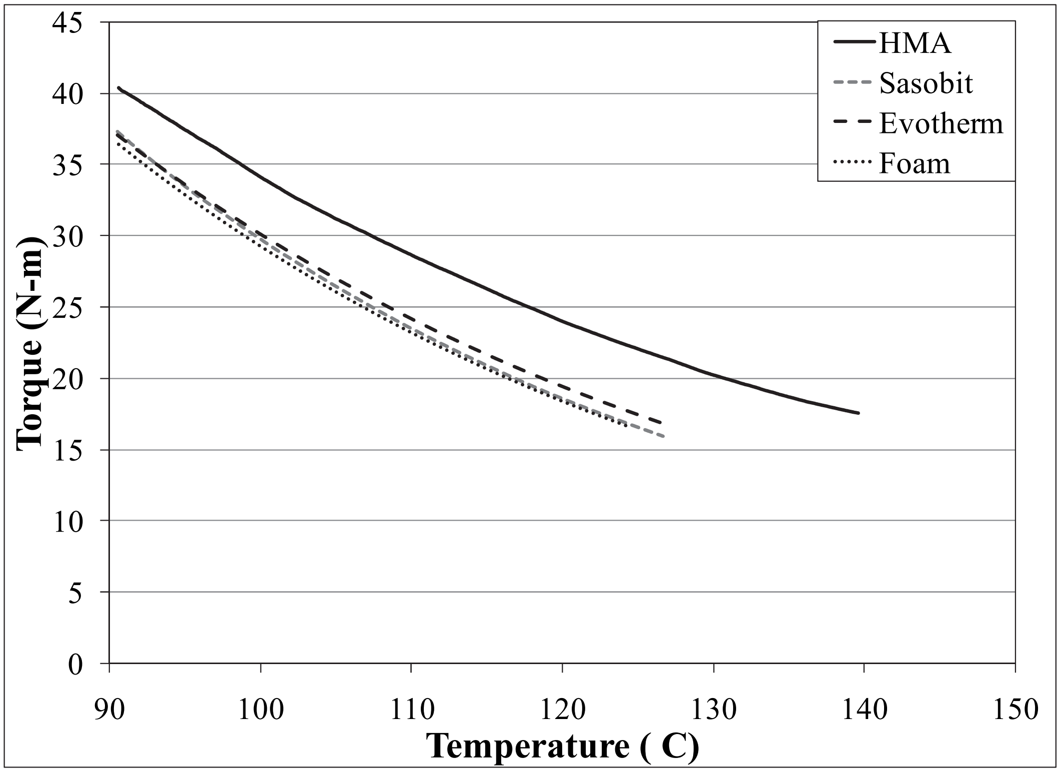


Figure 23. Workability data for 50% RAP limestone mixtures.



5 Conclusions and Recommendations

Conclusions

This laboratory study evaluated a range of aggregates, WMA technologies, and various RAP contents to determine the potential for using WMA technology for airfield pavements. Based on the data collected during this study, it can be concluded that WMA technologies can be used for airfield pavements.

The findings from this study were compiled in two ETLs. The first ETL was published in August 2011, ETL 11-3, and it had the purpose of introducing the concept of WMA technologies to the Air Force. It summarizes the main findings from the literature review and provides general information about the technologies that are available, benefits, research and construction projects, performance, and some general guidance. The second ETL presents more specific guidance on the use of WMA for airfield pavements, and it is based on the WMA guide specification that was developed in this study. The WMA guide specification is very similar to the current HMA specification for airfields, UFGS 32 12 15, with the main difference being production and compaction temperatures and the consideration of the WMA additives. These last two documents are currently under review and are expected to be published by spring 2012. It is expected that when these documents become available, the WMA work on airfields will increase.

Specific conclusions from the laboratory testing conducted in this study are:

- The measured increase in high-temperature grade of the binder when RAP was added to the mixes was noticeably higher than the measured increase in low-temperature grade of the binder. This indicates generally improved rut resistance of high RAP content mixes but only a limited increase in thermal cracking susceptibility.
- WMA technology can be used with high RAP content to produce mixtures that will be resistant to rutting. The binder will be stiffer for the high RAP contents, greatly reducing the potential for rutting.
- Susceptibility to thermal cracking does not appear to be a concern for WMA without RAP. Mixtures with high RAP content appear to be slightly more susceptible to thermal cracking. The high RAP content stiffens the asphalt binder, slightly increasing the low-temperature

grade of the asphalt; however, the effects of this on actual field performance are not clear.

- Warm mixes have typically been shown to be susceptible to water damage. WMA technology can be used with high RAP content to produce mixtures that are more resistant to moisture damage. Based on TSR testing, increasing the RAP content generally increases the resistance of a mix to moisture damage.
- Based on the Cantabro test, one would expect high RAP content mixes to be more susceptible to durability issues. Literature indicates that so far this has not been observed in the field, but additional monitoring of high RAP sections is needed to determine if durability is a problem or not.
- WMA mixes are potentially more workable than HMA mixes for all RAP contents based on laboratory testing, but the relationship of laboratory workability results to a mix's ability to achieve desired density during construction is not known.

Based on the data contained in this report, the two primary issues for WMA that need to be addressed are rutting under aircraft loadings and moisture damage susceptibility. The addition of RAP to the mix has the potential to help with both of these issues but could potentially cause reduced low-temperature performance and introduce durability issues. However, the extent of these issues may be small for moderate RAP contents of 25% or less. The evidence suggests that RAP in WMA is less susceptible to low-temperature performance problems than RAP with HMA. At this time, it is not possible to translate the laboratory results for durability or workability to estimated field performance.

Recommendations

The use of WMA for airfield asphalt pavements is recommended. Each Air Force Command should consider selecting at least one project for WMA technology per year to be constructed within the Command. As more airfield projects are constructed using WMA, more data can be collected to characterize these technologies and their performances under aircraft loading.

Further research to evaluate WMA for airfields is also recommended. The evaluation should include both laboratory testing and construction of test sections subjected to full-scale accelerated loading. The laboratory evaluation component should incorporate the following recommendations:

- Evaluate laboratory rutting with test conditions more representative of airfield loading conditions.
- Moisture damage testing should be expanded to include a wheel tracking test in addition to TSR.
- Evaluate other WMA technologies in addition to those tested herein.

References

Alvarez, A. E., A. E. Martin, C. Estakhri, and R. Izzo. 2008. Evaluation of Durability Tools for Porous Friction Courses. *Transportation Research Board 87th Annual Meeting Compendium of Papers*, (DVD-ROM), Paper No. 08-2370. Washington, DC: Transportation Research Board.

Anderson, R M., G. Baumgardner, R. May, and G. Reinke. 2008. *Engineering Properties, Emissions, and Field Performance of Warm Mix Asphalt Technologies*. NCHRP 9-47. Washington, DC: Transportation Research Board.

Austerman, A. J., W. S. Mogawer, and R. Bonaquist. 2009. Evaluating the Effects of Warm Mix Asphalt Technology Additive Dosages on the Workability and Durability of Asphalt Mixtures Containing Recycled Asphalt Pavement. *Transportation Research Board 88th Annual Meeting Compendium of Papers*, (DVD-ROM), Paper No. 09-1279. Washington, DC: Transportation Research Board.

Azari, H. 2010. *Precision Estimates of AASHTO T 283: Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage*. NCHRP Web-Only Document 166, National Cooperative Highway Research Program. Washington, DC: Transportation Research Board of the National Academies.

Bennert, T., G. Reinke, W. Mogawer, and K. Mooney. 2010. Assessment of Workability and Compactability of Warm-Mix Asphalt. *Transportation Research Record No. 2180*. Washington, DC: Transportation Research Board.

Bonaquist, R. 2011. Mix Design Practices for Warm Mix Asphalt. *National Cooperative Highway Research Program*, NCHRP Report 691. Washington, DC: Transportation Research Board.

Brown, D. C. 2010. The Extra Benefits of Warm-Mix Asphalt. *Modern Contractor Solutions*. Birmingham, AL: Highlands Publications, Inc.

Brown, E. R. 1984. *Evaluation of Properties of Recycled Asphalt Concrete Hot Mix*. Final Report GL-84-2. Vicksburg, MS: US Army Waterways Experiment Station.

Brown, E. R., P. S. Kandhal, and J. Zhang. 2001. *Performance Testing for Hot Mix Asphalt*. NCAT Report 01-05. Auburn, AL: National Center for Asphalt Technology.

Cooley Jr., L. A. 2003. *Evaluation of Pavement Permeability in Mississippi*. Auburn, AL: National Center for Asphalt Technology.

D'Angelo, J. D., E. Harm, J. Bartoszek, G. Baumgardner, M. Corrigan, J. Cowsert, T. Harman, M. Jamshidi, W. Jones, D. Newcomb, B. Prowell, R. Sines, and B. Yeaton. 2008. *Warm-Mix Asphalt: European Practice*. FHWA Report No. FHWA-PL-08-007. Washington, DC: Federal Highway Administration.

Doyle, J. D., and I. H. Howard. 2011a. Evaluation of the Cantabro Durability Test for Dense Graded Asphalt. In *Proceedings of Geo-Frontiers 2011*, Advances in Geotechnical Engineering-Geotechnical Special Publication No. 211 (CD-ROM), American Society of Civil Engineers, pp. 4563-4572.

Doyle, J. D., and I. L. Howard. 2011b. Factors Affecting Measurement of Effective Specific Gravity for Reclaimed Asphalt Pavement. Technical Note for *International Journal of Pavement Research and Technology*, In Press.

Gudimettla, J. M., L. A. Cooley, Jr., and E. R. Brown. 2003. *Workability of Hot Mix Asphalt*. NCAT Report 03-03. Auburn, AL: National Center for Asphalt Technology.

Gui-ping, H., and W. Wing-gun. 2006. Laboratory Study on Permanent Deformation of Foamed Asphalt Mix Incorporating Reclaimed Asphalt Pavement Materials. *Construction and Building Materials*, 21:1809-1819.

Haas, R. C. G., and W. A. Phang. 1988. Relationships between Mix Characteristics and Low-Temperature Pavement Cracking. *Asphalt Paving Technology: Journal of the Association of Asphalt Paving Technologists*, (57) 290-319.

Hearon, A., and S. Diefenderfer. 2008. Laboratory Evaluation of Warm Asphalt Properties and Performance. *Airfield and Highway Pavements, Proceedings of the Airfield and Highway Pavements Conference*. Bellevue, WA: American Society of Civil Engineers.

Hurley, G. C., and B. D. Prowell. 2005. *Evaluation of Sasobit® for use in Warm Mix Asphalt*. NCAT Report No. 05-06. Auburn, AL: National Center for Asphalt Technology.

Huang, B., G. Li, D. Vukosavljevic, X. Shu, and B. K. Egan. 2005. Laboratory Investigation of Mixing Hot-Mix Asphalt with Reclaimed Asphalt Pavement. *Transportation Research Record No. 1929*. Washington, DC: Transportation Research Board.

Jung, D., and T. S. Vinson. 1993. Low Temperature Cracking Resistance of Asphalt Concrete Mixtures. *Asphalt Paving Technology: Journal of the Association of Asphalt Paving Technologists*, (62) 54-92.

Kandhal, P. S., S. S. Rao, D. E. Watson, and B. Young. 1995. Performance of Recycled Hot-Mix Asphalt Mixtures in Georgia. *Transportation Research Record No. 1507*. Washington, DC: National Research Council.

Kanitpong, K., K. Nam, W. Martono, and H. Bahia. 2008. Evaluation of a Warm-Mix Asphalt Additive. In *Proceedings of the Institution of Civil Engineers,* Construction Materials, 161:1-8.

Kim, K. W., and H. M. El Hussein. 1995. Effect of Differential Thermal Contraction on Fracture Toughness of Asphalt Materials at Low Temperatures. *Asphalt Paving Technology: Journal of the Association of Asphalt Paving Technologists*, (64) 474-499.

Kraus, Z. R. 2008. The Morphology of Polymer Modified Asphalt and its Relationship to Rheology and Durability. MS Thesis. College Station, TX: Texas A&M University.

Kvasnak, A., R. West, J. Moore, J. Nelson, P. Turner, and N. Tran. 2009. Case Study of Warm Mix Asphalt Moisture Susceptibility in Birmingham. *Transportation Research Board 88th Annual Meeting Compendium of Papers*, (DVD-ROM), Paper No. 09-3703. Washington, DC: Transportation Research Board.

Kvasnak, A., A. Taylor, J. M. Signore, and S. A. Bukhari. 2010. *Evaluation of Gencor Green Machine Ultrafoam GX: Final Report*. NCAT Report 10-03. Auburn, AL: National Center for Asphalt Technology.

Lisican, E. 2010. Dream Liner Logan Airport first to lay down ideal asphalt surface. *Asphalt Today*. Arlington Heights, IL: Scranton Gillette Communications.

Li, X., T. R. Clyne, and M. O. Marasteanu. 2004. *Recycled Asphalt Pavement (RAP) Effects on Binder and Mixture Quality*. Report No. MN/RC – 2005-02. Minnesota Department of Transportation, Research Services Section.

Li, X., M. O. Marasteanu, W. Christopher, and T. R. Clyne. 2008. Effect of RAP (Proportion and Type) and Binder Grade on the Properties of Asphalt Mixtures. *Transportation Research Board 86th Annual Meeting Compendium of Papers*, (CD-ROM), TRB, National Research Council.

Mallick, R. B., J. E. Bradley, and R. L. Bradbury. 2007. Evaluation of Heated Reclaimed Asphalt Pavement Material and Wax-Modified Asphalt for use in Recycled Hot-Mix Asphalt. *Transportation Research Record No. 1998*. Washington, DC: Transportation Research Board.

Mallick, R. B., P. S. Kandhal, and R. L. Bradbury. 2008. Using Warm Mix Asphalt Technology to Incorporate High Percentage of Reclaimed Asphalt Pavement Material in Asphalt Mixes. *Transportation Research Record: Journal of the Transportation Research Board*, *No. 2051*. pp. 71-79.

MeadWestvaco. 2011. *Evotherm Warm Mix Asphalt Product Brochure*. <http://www.meadwestvaco.com/mwv/groups/content/documents/document/mwv006575.pdf> (Accessed March 26, 2011).

Meyers, F., R. Tessier, R. Haas, and T. W. Kennedy. 1983. *Study of Hot Mix Recycling of Asphalt Pavements*. Report 2964 E. Ottawa, Ontario: Roads and Transportation Association of Canada.

National Asphalt Pavement Association (NAPA) 2011. *Warm Mix Asphalt – WMA Technologies*. <http://www.warmmixasphalt.com/WmaTechnologies.aspx> (Accessed October 21, 2011)

Ozer, H., I. L. Al-Qadi, S. H. Carpenter, Q. Aurangzeb, G. L. Roberts, and J. Trepanier. 2009. Evaluation of RAP Impact on Hot-Mix Asphalt Design and Performance. *Asphalt Paving Technology: Journal of the Association of Asphalt Paving Technologists*, (78) 317-351.

Prowell, B. D., and G. C. Hurley. 2007. *Warm-Mix Asphalt: Best Practices*. Landham, MD: National Asphalt Pavement Association (NAPA).

Prowell, B. D, G. C. Hurley, and E. Crews. 2007. Field Performance of Warm-Mix Asphalt at National Center for Asphalt Technology Test Track. *Transportation Research Record No.1998*. Washington, DC: Transportation Research Board.

Roque, R., D. R. Hiltunen, and W. G. Buttlar. 1995. Thermal Cracking Performance and Design of Mixtures Using Superpave. *Asphalt Paving Technology: Journal of the Association of Asphalt Paving Technologists*, (64) 718-735.

Sasol Wax. 2004. *The Bitumen Additive for Highly Stable Easily Compactable Asphalts*. Product Information 124, Sasol Wax GmbH. <http://www.sasolwax.com/data/sasolwax_/Bitumen%20Modification/Sasobit%20since%201997.pdf> (Accessed Nov 01, 2007).

Su, K., R. Maekawa, and Y. Hachiya. 2009. Laboratory Evaluation of WMA Mixture for use in Airport Pavement Rehabilitation. *Construction and Building Materials*, (23) 2709-2714.

Tao, M., and R. B. Mallick. 2009. Effects of Warm-Mix Asphalt Additives on Workability and Mechanical Properties of Reclaimed Asphalt Pavement Material. *Transportation Research Record No. 2126*. Washington, DC: Transportation Research Board.

Transportation Research Board (TRB). 2011a. *National Cooperative Highway Research Program Research Results Digest 351*. Washington, DC: Transportation Research Board of the National Academies.

Transportation Research Board (TRB). 2011b. *National Cooperative Highway Research Program (NCHRP) Projects*. <http://www.trb.org/NCHRP/NCHRPProjects.aspx> (Accessed November 15, 2011).

United States Army Corps of Engineers (USACE). 2010. *Hot-Mix Asphalt (HMA) for Airfields*. Unified Facilities Guide Specification UFGS-32 12 15.

Vinson, T. S., V. C. Janoo, and R. C. G. Haas. 1989. *Low Temperature and Thermal Fatigue Cracking*. SHRP Summary Report SHRP-A-306.

Watson, D. E., K. A. Moore, K. Williams, and L. A. Cooley Jr. 2003. Refinement of New-Generation Open-Graded Friction Course Mix Design. *Transportation Research Record No. 1832*. Washington, DC: Transportation Research Board.

Watson, D. E., L. A. Cooley Jr., K. A. Moore, and K. Williams. 2004. Laboratory Performance Testing of Open-Graded Friction Course Mixtures. *Transportation Research Record No.1891*. Washington, DC: Transportation Research Board.

West, R., A. Kvasnak, N. Tran, B. Powell, and P. Turner. 2009. Testing of Moderate and High Reclaimed Asphalt Content Pavement Content Mixes. *Transportation Research Record No. 2126*. Washington, DC: Transportation Research Board.

Xiao, F., J. Jordan, and S. N. Amirkhanian. 2009. Laboratory Investigation of Moisture Damage in Warm-Mix Asphalt Containing Moist Aggregate. *Transportation Research Record No. 2126*. Washington, DC: Transportation Research Board.

You, Z., and S. W. Goh. 2008. Laboratory Evaluation of Warm Mix Asphalt: a Preliminary Study. *International Journal of Pavement Research and Technology*, (1) 1: 34-40.

Zaniewski, J., and A. G. Viswanathan. 2006. *Investigation of Moisture Sensitivity of Hot Mix Asphalt Concrete*. Report Submitted to West Virginia Division of Highways.

Zofka, A., M. O. Marasteanu, T. R. Clyne, X. Li, and O. Hoffmann. 2004. *Development of Simple Asphalt Test for Determination of RAP Blending Charts*. Report No. MN/RC-2004-44. St. Paul, MN: Minnesota Department of Transportation.

Appendix A: Raw Test Data

Table A1. APA test data for mixtures 1 to 12.

Mix No.	Rep	Air Voids (V_a) (%)				Rut @ 8000 cycles (mm)	
		Front	Rear	Row Avg.	Avg.	Total	Avg.
1	1	7.5	7.5	7.5	7.5	6.5	6.5
	2	7.6	7.4	7.5		6.0	
	3	7.5	7.6	7.6		7.0	
2	1	7.2	7.4	7.3	7.3	5.8	6.0
	2	7.1	7.3	7.2		5.2	
	3	7.3	7.3	7.3		6.9	
3	1	7.7	7.8	7.8	7.7	8.0	7.8
	2	7.5	7.7	7.6		7.7	
	3	7.7	7.6	7.7		7.7	
4	1	6.8	6.8	6.8	6.8	9.8	7.1
	2	6.7	6.5	6.6		6.2	
	3	7.1	6.7	6.9		5.5	
5	1	6.7	7.0	6.9	6.4	3.3	3.0
	2	6.0	6.2	6.1		2.9	
	3	6.2	6.4	6.3		2.9	
6	1	6.1	6.5	6.3	6.7	3.9	4.4
	2	6.8	6.8	6.8		4.5	
	3	6.9	7.2	7.1		4.8	
7	1	6.5	7.6	7.1	6.7	3.4	3.7
	2	7.5	6.6	7.1		3.1	
	3	5.9	6.3	6.1		4.7	
8	1	7.3	7.0	7.2	7.4	5.7	5.6
	2	7.5	7.4	7.5		5.4	
	3	7.5	7.5	7.5		5.6	
9	1	7.5	7.5	7.5	7.5	3.6	3.6
	2	7.5	7.5	7.5		4.0	
	3	7.4	7.5	7.5		3.2	
10	1	7.4	7.4	7.4	7.5	4.2	4.4
	2	7.5	7.4	7.5		4.2	
	3	7.6	7.6	7.6		4.8	
11	1	7.1	7.1	7.1	7.1	2.9	2.7
	2	7.1	7.3	7.2		2.6	
	3	6.9	7.2	7.1		2.5	
12	1	6.5	6.9	6.7	6.8	3.6	2.9
	2	6.9	6.7	6.8		2.8	
	3	6.7	6.9	6.8		2.3	

Table A2. APA test data for mixtures 13 to 24.

Mix No.	Rep	Air Voids (V_a) (%)				Rut @ 8000 cycles (mm)	
		Front	Rear	Row Avg.	Avg.	Total	Avg.
13	1	7.1	7.0	7.1	7.1	6.9	6.9
	2	---[a]	---[a]	---[a]		---[a]	
	3	---[a]	---[a]	---[a]		---[a]	
14	1	7.1	7.1	7.1	7.1	4.7	5.4
	2	7.2	7.2	7.2		5.2	
	3	6.9	7.2	7.1		6.2	
15	1	7.0	7.4	7.2	7.3	4.4	4.7
	2	7.2	7.1	7.2		4.9	
	3	7.4	7.4	7.4		4.8	
16	1	7.2	7.3	7.3	6.9	10.3	8.8
	2	7.0	6.5	6.8		8.3	
	3	6.6	6.8	6.7		7.9	
17	1	7.3	6.8	7.1	6.8	4.3	4.0
	2	7.0	6.7	6.9		4.2	
	3	6.5	6.6	6.6		3.6	
18	1	6.5	6.6	6.6	6.7	3.1	2.6
	2	6.7	6.5	6.6		2.6	
	3	7.1	6.8	7.0		2.2	
19	1	6.5	6.8	6.7	6.7	5.4	5.1
	2	6.6	6.6	6.6		4.8	
	3	7.1	6.5	6.8		5.0	
20	1	7.6	7.5	7.6	7.4	4.2	4.4
	2	7.5	7.3	7.4		4.2	
	3	7.3	7.4	7.4		4.8	
21	1	6.6	7.4	7.0	6.9	1.7	1.7
	2	6.9	6.8	6.9		1.9	
	3	7.0	6.6	6.8		1.6	
22	1	6.9	7.0	7.0	6.9	2.2	2.3
	2	6.9	7.0	7.0		2.1	
	3	7.0	6.8	6.9		2.5	
23	1	7.1	6.8	7.0	6.8	3.3	3.6
	2	6.7	6.8	6.8		3.8	
	3	7.0	6.6	6.8		3.9	
24	1	7.0	7.0	7.0	7.3	4.6	5.0
	2	7.5	7.5	7.5		5.3	
	3	---[a]	---[a]	---[a]		---[a]	

a) Data not available.

Table A3. Cantabro test data for mixtures 1 to 12.

Mix No.	Rep	Air Voids		Mass Loss				
		V_a (%)	Avg.	Temp (C)	W_1 (g)	W_2 (g)	*ML* (%)	Avg.
1	1	4.7	**4.3**	25.7	4820.0	4563.5	5.3	**5.7**
	2	3.7		25.4	4832.2	4589.7	5.0	
	3	4.5		25.8	4836.8	4513.5	6.7	
2	1	4.4	**4.5**	25.8	4843.1	4460.5	7.9	**7.5**
	2	4.7		25.7	4847.8	4516.8	6.8	
	3	4.4		25.5	4832.5	4454.8	7.8	
3	1	4.4	**4.2**	25.8	4848.8	4577.8	5.6	**5.0**
	2	4.1		25.5	4803.4	4551.4	5.2	
	3	4.1		25.8	4812.1	4615.3	4.1	
4	1	4.1	**3.8**	25.0	4834.9	4570.5	5.5	**5.2**
	2	3.6		24.4	4827.2	4562.4	5.5	
	3	3.7		24.4	4844.7	4612.5	4.8	
5	1	3.0	**3.4**	25.8	4807.9	4320.6	10.1	**11.8**
	2	3.9		25.8	4802.8	4216.4	12.2	
	3	3.2		25.8	4812.3	4188.3	13.0	
6	1	3.2	**3.2**	25.3	4819.4	4239.8	12.0	**12.5**
	2	3.2		24.6	4801.7	4140.6	13.8	
	3	3.3		24.7	4817.8	4249.8	11.8	
7	1	3.1	**3.4**	25.2	4824.8	4305.9	10.8	**10.6**
	2	4.0		25.6	4812.7	4309.0	10.5	
	3	3.1		24.6	4821.6	4317.3	10.5	
8	1	3.2	**3.5**	24.7	4863.3	4267.1	12.3	**11.5**
	2	3.6		24.6	4857.1	4297.3	11.5	
	3	3.7		24.9	4847.4	4322.5	10.8	
9	1	3.6	**3.8**	25.8	4701.2	3910.7	16.8	**17.4**
	2	4.1		25.6	4838.4	4003.2	17.3	
	3	3.6		25.7	4820.0	3940.6	18.2	
10	1	4.5	**4.0**	25.2	4706.1	3892.3	17.3	**17.0**
	2	3.5		25.6	4699.6	3885.7	17.3	
	3	4.2		25.6	4688.1	3924.3	16.3	
11	1	3.8	**3.9**	25.9	4700.6	3899.6	17.0	**16.9**
	2	4.3		25.9	4677.5	3885.2	16.9	
	3	3.7		25.7	4699.0	3907.0	16.9	
12	1	4.0	**4.1**	25.9	4682.7	3909.3	16.5	**15.3**
	2	4.7		25.3	4695.5	4017.0	14.5	
	3	3.6		25.4	4714.5	4005.1	15.0	

Table A4. Cantabro test data for mixtures 13 to 24.

Mix No.	Rep	Air Voids		Mass Loss				
		V_a (%)	Avg.	Temp (C)	W_1 (g)	W_2 (g)	*ML* (%)	Avg.
13	1	3.4	**3.7**	25.1	4443.3	4141.5	6.8	**8.3**
	2	4.0		24.3	4464.8	4067.6	8.9	
	3	3.6		25.7	4458.4	4052.1	9.1	
14	1	4.5	**4.1**	25.5	4443.8	3898.1	12.3	**11.9**
	2	4.2		25.3	4411.6	3839.4	13.0	
	3	3.7		25.3	4408.6	3944.6	10.5	
15	1	5.0	**4.7**	25.2	4423.4	4067.6	8.0	**8.3**
	2	4.8		25.2	4429.4	3989.5	9.9	
	3	4.1		25.8	4445.0	4136.1	6.9	
16	1	4.1	**3.9**	25.5	4381.2	3919.2	10.5	**9.3**
	2	3.4		25.8	4406.2	4073.7	7.5	
	3	4.1		25.5	4382.0	3952.9	9.8	
17	1	4.2	**3.8**	25.4	4457.2	3881.0	12.9	**13.9**
	2	2.9		25.3	4407.3	3861.3	12.4	
	3	4.3		25.3	4465.8	3731.8	16.4	
18	1	4.0	**3.9**	25.3	4403.2	3594.6	18.4	**15.8**
	2	3.8		25.5	4396.3	3753.9	14.6	
	3	3.7		25.7	4393.0	3765.0	14.3	
19	1	3.6	**3.9**	25.4	4396.2	3846.9	12.5	**12.1**
	2	4.5		25.5	4390.1	3831.6	12.7	
	3	3.6		24.7	4402.6	3918.5	11.0	
20	1	4.0	**3.8**	25.8	4405.1	3849.0	12.6	**12.2**
	2	3.4		25.5	4406.5	3898.3	11.5	
	3	4.2		25.4	4386.3	3836.1	12.5	
21	1	4.5	**3.9**	25.0	4410.0	3539.6	19.7	**19.9**
	2	3.2		25.6	4402.9	3519.1	20.1	
	3	3.9		24.3	4425.6	3548.8	19.8	
22	1	3.6	**3.3**	25.3	4434.8	3604.9	18.7	**17.4**
	2	3.3		25.2	4438.2	3696.3	16.7	
	3	3.1		25.7	4424.3	3679.5	16.8	
23	1	4.6	**4.2**	24.3	4452.1	3673.0	17.5	**15.2**
	2	3.6		25.7	4431.0	3846.9	13.2	
	3	4.3		25.3	4417.9	3762.4	14.8	
24	1	4.0	**4.2**	25.7	4378.8	3667.2	16.3	**18.4**
	2	4.8		25.0	4368.6	3445.3	21.1	
	3	3.8		25.1	4385.0	3607.1	17.7	

Table A5. BBR test data for mixtures 1 to 4.

Mix No.	Test Temp	Rep	V_a (%)	Stiffness (GPa) and Test Time 8 s	15 s	30 s	60 s	120 s	240 s	480 s	960 s	Slope (m-value) and Test Time 8 s	15 s	30 s	60 s	120 s	240 s	480 s	960 s
1	-06 C	1	3.2	9.73	8.90	7.96	7.02	6.10	5.23	4.42	3.69	0.132	0.151	0.172	0.192	0.213	0.233	0.254	0.274
		2	3.1	11.47	10.41	9.18	7.94	6.74	5.62	4.60	3.69	0.143	0.167	0.194	0.221	0.248	0.276	0.303	0.330
		Avg.	3.1	10.60	9.66	8.57	7.48	6.42	5.42	4.51	3.69	0.137	0.159	0.183	0.207	0.231	0.254	0.278	0.302
	-12 C	1	3.2	12.17	11.41	10.50	9.53	8.53	7.54	6.58	5.67	0.094	0.112	0.131	0.150	0.169	0.188	0.208	0.227
		2	3.1	19.48	17.98	16.22	14.43	12.65	10.93	9.30	7.80	0.118	0.137	0.159	0.180	0.202	0.223	0.245	0.266
		Avg.	3.1	15.82	14.69	13.36	11.98	10.59	9.24	7.94	6.73	0.106	0.125	0.145	0.165	0.186	0.206	0.226	0.246
2	-06 C	1	4.8	9.66	8.70	7.63	6.57	5.55	4.62	3.77	3.03	0.155	0.178	0.203	0.229	0.254	0.280	0.305	0.331
		2	3.8	10.38	9.38	8.24	7.11	6.02	5.01	4.09	3.28	0.149	0.173	0.200	0.226	0.252	0.279	0.305	0.332
		Avg.	4.3	10.02	9.04	7.93	6.84	5.79	4.81	3.93	3.16	0.152	0.175	0.201	0.227	0.253	0.279	0.305	0.331
	-12 C	1	4.8	15.93	14.89	13.66	12.37	11.05	9.75	8.49	7.30	0.098	0.116	0.135	0.154	0.172	0.191	0.210	0.229
		2	3.8	17.84	16.69	15.34	13.93	12.50	11.09	9.72	8.42	0.097	0.113	0.130	0.147	0.164	0.182	0.199	0.216
		Avg.	4.3	16.88	15.79	14.50	13.15	11.78	10.42	9.10	7.86	0.098	0.114	0.132	0.150	0.168	0.187	0.205	0.223
3	-06 C	1	4.4	9.29	8.21	7.00	5.83	4.74	3.76	2.92	2.21	0.182	0.213	0.247	0.282	0.316	0.350	0.384	0.419
		2	4.9	9.42	8.21	6.89	5.64	4.51	3.52	2.68	1.99	0.203	0.236	0.271	0.307	0.343	0.379	0.415	0.450
		Avg.	4.7	9.36	8.21	6.95	5.74	4.62	3.64	2.80	2.10	0.193	0.224	0.259	0.294	0.329	0.365	0.400	0.435
	-12 C	1	4.4	13.57	12.49	11.22	9.91	8.60	7.34	6.16	5.08	0.119	0.142	0.166	0.190	0.215	0.239	0.264	0.288
		2	4.9	15.10	13.99	12.65	11.24	9.81	8.43	7.11	5.90	0.110	0.133	0.158	0.183	0.208	0.233	0.257	0.282
		Avg.	4.7	14.34	13.24	11.93	10.57	9.21	7.88	6.64	5.49	0.115	0.137	0.162	0.187	0.211	0.236	0.261	0.285
4	-06 C	1	4.5	11.20	9.92	8.50	7.13	5.84	4.69	3.68	2.83	0.179	0.209	0.241	0.273	0.305	0.337	0.369	0.401
		2	3.7	9.27	8.17	6.93	5.73	4.61	3.62	2.76	2.06	0.183	0.218	0.256	0.293	0.331	0.369	0.407	0.445
		Avg.	4.1	10.23	9.04	7.71	6.43	5.23	4.15	3.22	2.44	0.181	0.213	0.248	0.283	0.318	0.353	0.388	0.423
	-12 C	1	4.5	12.50	11.50	10.33	9.16	7.99	6.88	5.83	4.88	0.124	0.143	0.164	0.186	0.207	0.228	0.249	0.271
		2	3.7	16.71	15.42	13.89	12.30	10.71	9.17	7.73	6.40	0.116	0.139	0.163	0.187	0.212	0.236	0.260	0.285
		Avg.	4.1	14.61	13.46	12.11	10.73	9.35	8.03	6.78	5.64	0.120	0.141	0.164	0.187	0.209	0.232	0.255	0.278

Table A6. BBR test data for mixtures 5 to 8.

Mix	Test		V_a	Stiffness (GPa) and Test Time								Slope (m-value) and Test Time							
No.	Temp	Rep	(%)	8 s	15 s	30 s	60 s	120 s	240 s	480 s	960 s	8 s	15 s	30 s	60 s	120 s	240 s	480 s	960 s
5	-06 C	1	2.9	17.20	15.91	14.47	13.02	11.59	10.21	8.91	7.69	0.116	0.130	0.145	0.160	0.175	0.190	0.205	0.220
		2	3.7	16.03	14.76	13.34	11.93	10.55	9.24	8.00	6.85	0.124	0.138	0.153	0.169	0.184	0.200	0.215	0.231
		Avg.	**3.3**	**16.61**	**15.34**	**13.90**	**12.47**	**11.07**	**9.72**	**8.45**	**7.27**	**0.120**	**0.134**	**0.149**	**0.164**	**0.180**	**0.195**	**0.210**	**0.225**
	-12 C	1	2.9	22.71	21.33	19.71	18.02	16.31	14.61	12.95	11.36	0.093	0.107	0.122	0.136	0.151	0.166	0.181	0.196
		2	3.7	21.88	20.56	19.04	17.50	15.96	14.43	12.96	11.54	0.094	0.105	0.116	0.128	0.139	0.150	0.162	0.173
		Avg.	**3.3**	**22.30**	**20.94**	**19.37**	**17.76**	**16.13**	**14.52**	**12.95**	**11.45**	**0.094**	**0.106**	**0.119**	**0.132**	**0.145**	**0.158**	**0.171**	**0.185**
6	-06 C	1	3.3	15.47	14.42	13.18	11.88	10.56	9.26	8.01	6.84	0.103	0.121	0.141	0.160	0.180	0.199	0.219	0.239
		2	4.2	15.56	14.52	13.27	11.97	10.65	9.35	8.10	6.92	0.102	0.120	0.140	0.159	0.179	0.199	0.219	0.239
		Avg.	**3.8**	**15.52**	**14.47**	**13.23**	**11.92**	**10.61**	**9.31**	**8.05**	**6.88**	**0.103**	**0.120**	**0.140**	**0.160**	**0.179**	**0.199**	**0.219**	**0.239**
	-12 C	1	3.3	17.89	17.01	15.94	14.81	13.63	12.44	11.25	10.08	0.074	0.086	0.100	0.113	0.127	0.140	0.154	0.167
		2	4.2	18.86	17.81	16.61	15.38	14.15	12.92	11.72	10.56	0.087	0.096	0.106	0.116	0.126	0.136	0.146	0.156
		Avg.	**3.8**	**18.37**	**17.41**	**16.28**	**15.10**	**13.89**	**12.68**	**11.49**	**10.32**	**0.080**	**0.091**	**0.103**	**0.114**	**0.126**	**0.138**	**0.150**	**0.161**
7	-06 C	1	3.9	16.31	15.09	13.63	12.10	10.57	9.08	7.67	6.37	0.112	0.134	0.159	0.183	0.207	0.231	0.256	0.280
		2	3.6	16.46	15.11	13.58	12.06	10.57	9.15	7.82	6.61	0.127	0.144	0.163	0.182	0.201	0.220	0.239	0.257
		Avg.	**3.8**	**16.39**	**15.10**	**13.61**	**12.08**	**10.57**	**9.11**	**7.74**	**6.49**	**0.120**	**0.139**	**0.161**	**0.182**	**0.204**	**0.226**	**0.247**	**0.269**
	-12 C	1	3.9	18.85	17.91	16.75	15.51	14.21	12.89	11.57	10.28	0.075	0.089	0.103	0.118	0.133	0.147	0.162	0.176
		2	3.6	17.12	16.24	15.13	13.90	12.61	11.29	9.97	8.70	0.075	0.093	0.112	0.131	0.150	0.169	0.189	0.208
		Avg.	**3.8**	**17.99**	**17.07**	**15.94**	**14.71**	**13.41**	**12.09**	**10.77**	**9.49**	**0.075**	**0.091**	**0.108**	**0.125**	**0.141**	**0.158**	**0.175**	**0.192**
8	-06 C	1	2.9	13.41	12.36	11.14	9.88	8.64	7.43	6.30	5.26	0.119	0.139	0.161	0.183	0.205	0.227	0.249	0.271
		2	3.7	14.17	13.00	11.62	10.21	8.81	7.46	6.21	5.08	0.127	0.150	0.175	0.201	0.226	0.251	0.277	0.302
		Avg.	**3.3**	**13.79**	**12.68**	**11.38**	**10.05**	**8.72**	**7.45**	**6.26**	**5.17**	**0.123**	**0.145**	**0.168**	**0.192**	**0.216**	**0.239**	**0.263**	**0.287**
	-12 C	1	2.9	18.00	16.95	15.67	14.31	12.90	11.49	10.10	8.77	0.088	0.104	0.122	0.140	0.158	0.176	0.194	0.212
		2	2.7	15.96	14.97	13.79	12.55	11.28	10.02	8.80	7.63	0.095	0.110	0.127	0.145	0.162	0.179	0.197	0.214
		Avg.	**3.3**	**16.98**	**15.96**	**14.73**	**13.43**	**12.09**	**10.75**	**9.45**	**8.20**	**0.091**	**0.107**	**0.125**	**0.143**	**0.160**	**0.178**	**0.196**	**0.213**

Table A7. BBR test data for mixtures 9 to 12.

Mix	Test		V_a	Stiffness (GPa) and Test Time								Slope (m-value) and Test Time							
No.	Temp	Rep	(%)	8 s	15 s	30 s	60 s	120 s	240 s	480 s	960 s	8 s	15 s	30 s	60 s	120 s	240 s	480 s	960 s
9	-06 C	1	4.6	16.75	15.85	14.77	13.61	12.40	11.18	9.98	8.80	0.080	0.095	0.110	0.126	0.142	0.158	0.174	0.190
		2	3.7	17.47	16.66	15.67	14.60	13.48	12.33	11.17	10.03	0.067	0.080	0.094	0.108	0.122	0.136	0.150	0.164
		Avg.	**4.2**	**17.11**	**16.26**	**15.22**	**14.11**	**12.94**	**11.76**	**10.58**	**9.42**	**0.074**	**0.087**	**0.102**	**0.117**	**0.132**	**0.147**	**0.162**	**0.177**
	-12 C	1	4.6	24.67	23.66	22.35	20.89	19.31	17.66	15.99	14.32	0.062	0.075	0.090	0.104	0.119	0.134	0.149	0.163
		2	3.7	24.39	23.25	21.84	20.33	18.74	17.10	15.46	13.85	0.070	0.083	0.096	0.110	0.124	0.138	0.152	0.166
		Avg.	**4.2**	**24.53**	**23.45**	**22.10**	**20.61**	**19.02**	**17.38**	**15.72**	**14.09**	**0.066**	**0.079**	**0.093**	**0.107**	**0.122**	**0.136**	**0.150**	**0.165**
10	-06 C	1	5.6	14.78	13.88	12.83	11.74	10.65	9.57	8.51	7.50	0.094	0.106	0.120	0.134	0.148	0.161	0.175	0.189
		2	6.3	15.46	14.42	13.22	11.98	10.74	9.52	8.34	7.23	0.103	0.118	0.134	0.150	0.166	0.183	0.199	0.215
		Avg.	**5.9**	**15.12**	**14.15**	**13.02**	**11.86**	**10.69**	**9.54**	**8.43**	**7.37**	**0.098**	**0.112**	**0.127**	**0.142**	**0.157**	**0.172**	**0.187**	**0.202**
	-12 C	1	5.6	18.79	17.89	16.83	15.71	14.56	13.38	12.21	11.05	0.071	0.081	0.092	0.103	0.114	0.126	0.137	0.148
		2	6.3	18.33	17.44	16.37	15.21	14.00	12.77	11.53	10.32	0.073	0.085	0.099	0.113	0.126	0.140	0.153	0.167
		Avg.	**5.9**	**18.56**	**17.67**	**16.60**	**15.46**	**14.28**	**13.07**	**11.87**	**10.69**	**0.072**	**0.083**	**0.096**	**0.108**	**0.120**	**0.133**	**0.145**	**0.157**
11	-06 C	1	5.2	15.81	14.88	13.73	12.50	11.23	9.95	8.69	7.49	0.088	0.106	0.125	0.145	0.165	0.185	0.205	0.225
		2	5.9	15.74	14.81	13.70	12.54	11.36	10.17	9.01	7.90	0.090	0.104	0.120	0.137	0.153	0.169	0.185	0.201
		Avg.	**5.6**	**15.78**	**14.85**	**13.72**	**12.52**	**11.29**	**10.06**	**8.85**	**7.70**	**0.089**	**0.105**	**0.123**	**0.141**	**0.159**	**0.177**	**0.195**	**0.213**
	-12 C	1	5.2	16.66	15.86	14.96	14.04	13.12	12.21	11.30	10.42	0.075	0.081	0.088	0.095	0.101	0.108	0.115	0.122
		2	5.9	17.61	16.85	15.96	15.00	14.01	13.00	11.98	10.97	0.065	0.074	0.084	0.094	0.104	0.114	0.125	0.135
		Avg.	**5.6**	**17.13**	**16.36**	**15.46**	**14.52**	**13.57**	**12.60**	**11.64**	**10.69**	**0.070**	**0.078**	**0.086**	**0.094**	**0.103**	**0.111**	**0.120**	**0.128**
12	-06 C	1	4.0	17.92	16.78	15.46	14.11	12.75	11.42	10.12	8.89	0.098	0.111	0.125	0.139	0.153	0.167	0.181	0.195
		2	3.7	17.22	16.20	15.00	13.77	12.53	11.29	10.09	8.93	0.094	0.106	0.119	0.132	0.145	0.158	0.171	0.184
		Avg.	**3.8**	**17.57**	**16.49**	**15.23**	**13.94**	**12.64**	**11.35**	**10.10**	**8.91**	**0.096**	**0.108**	**0.122**	**0.136**	**0.149**	**0.163**	**0.176**	**0.190**
	-12 C	1	4.0	24.30	23.25	21.90	20.41	18.80	17.12	15.41	13.72	0.063	0.078	0.094	0.110	0.127	0.143	0.159	0.176
		2	3.7	21.91	21.09	20.01	18.75	17.38	15.92	14.41	12.90	0.053	0.068	0.085	0.102	0.118	0.135	0.152	0.169
		Avg.	**3.8**	**23.10**	**22.17**	**20.95**	**19.58**	**18.09**	**16.52**	**14.91**	**13.31**	**0.058**	**0.073**	**0.089**	**0.106**	**0.123**	**0.139**	**0.156**	**0.172**

Table A8. BBR test data for mixtures 13 to 16.

Mix No.	Test Temp	Rep	V_a (%)	Stiffness (GPa) and Test Time 8 s	15 s	30 s	60 s	120 s	240 s	480 s	960 s	Slope (m-value) and Test Time 8 s	15 s	30 s	60 s	120 s	240 s	480 s	960 s
13	-06 C	1	3.7	9.73	8.90	7.96	7.02	6.10	5.23	4.42	3.69	0.132	0.151	0.172	0.192	0.213	0.233	0.254	0.274
		2	4.3	11.90	10.85	9.64	8.41	7.22	6.10	5.06	4.13	0.136	0.158	0.183	0.208	0.232	0.257	0.282	0.306
		Avg.	**4.0**	**10.82**	**9.88**	**8.80**	**7.72**	**6.66**	**5.66**	**4.74**	**3.91**	**0.134**	**0.155**	**0.177**	**0.200**	**0.223**	**0.245**	**0.268**	**0.290**
	-12 C	1	3.7	12.17	11.41	10.50	9.53	8.53	7.54	6.58	5.67	0.094	0.112	0.131	0.150	0.169	0.188	0.208	0.227
		2	4.3	13.89	13.03	11.99	10.88	9.74	8.61	7.51	6.46	0.093	0.111	0.130	0.149	0.168	0.187	0.206	0.226
		Avg.	**4.0**	**13.03**	**12.22**	**11.24**	**10.20**	**9.14**	**8.08**	**7.04**	**6.06**	**0.094**	**0.111**	**0.130**	**0.150**	**0.169**	**0.188**	**0.207**	**0.226**
14	-06 C	1	4.4	11.72	10.73	9.58	8.41	7.25	6.15	5.12	4.19	0.129	0.152	0.177	0.202	0.227	0.252	0.277	0.303
		2	4.5	11.84	10.84	9.68	8.49	7.33	6.22	5.18	4.25	0.128	0.151	0.175	0.200	0.225	0.250	0.274	0.299
		Avg.	**4.4**	**11.78**	**10.79**	**9.63**	**8.45**	**7.29**	**6.18**	**5.15**	**4.22**	**0.129**	**0.151**	**0.176**	**0.201**	**0.226**	**0.251**	**0.276**	**0.301**
	-12 C	1	4.4	13.07	12.37	11.43	10.38	9.25	8.11	6.98	5.91	0.074	0.096	0.121	0.145	0.170	0.194	0.219	0.243
		2	4.5	15.24	14.32	13.22	12.06	10.87	9.67	8.50	7.38	0.090	0.106	0.124	0.142	0.159	0.177	0.195	0.213
		Avg.	**4.4**	**14.15**	**13.34**	**12.33**	**11.22**	**10.06**	**8.89**	**7.74**	**6.65**	**0.082**	**0.101**	**0.122**	**0.144**	**0.165**	**0.186**	**0.207**	**0.228**
15	-06 C	1	4.5	10.59	9.67	8.58	7.47	6.38	5.34	4.38	3.53	0.132	0.157	0.186	0.214	0.242	0.271	0.299	0.327
		2	4.5	6.84	6.23	5.49	4.74	4.00	3.30	2.66	2.10	0.139	0.169	0.202	0.235	0.268	0.300	0.333	0.366
		Avg.	**4.5**	**8.72**	**7.95**	**7.04**	**6.11**	**5.19**	**4.32**	**3.52**	**2.82**	**0.135**	**0.163**	**0.194**	**0.224**	**0.255**	**0.285**	**0.316**	**0.347**
	-12 C	1	4.5	16.88	15.84	14.55	13.16	11.73	10.29	8.89	7.56	0.091	0.111	0.134	0.156	0.178	0.200	0.222	0.244
		2	4.5	14.66	13.78	12.71	11.57	10.40	9.22	8.06	6.96	0.090	0.107	0.126	0.145	0.164	0.183	0.202	0.221
		Avg.	**4.5**	**15.77**	**14.81**	**13.63**	**12.37**	**11.06**	**9.75**	**8.48**	**7.26**	**0.091**	**0.109**	**0.130**	**0.150**	**0.171**	**0.191**	**0.212**	**0.232**
16	-06 C	1	3.9	10.20	9.20	8.05	6.90	5.78	4.75	3.82	3.00	0.149	0.177	0.208	0.238	0.269	0.299	0.330	0.361
		2	4.0	11.56	10.61	9.47	8.29	7.12	6.00	4.96	4.02	0.124	0.150	0.177	0.205	0.233	0.261	0.289	0.317
		Avg.	**4.0**	**10.88**	**9.91**	**8.76**	**7.59**	**6.45**	**5.38**	**4.39**	**3.51**	**0.137**	**0.163**	**0.192**	**0.222**	**0.251**	**0.280**	**0.309**	**0.339**
	-12 C	1	3.9	13.63	12.84	11.86	10.81	9.72	8.62	7.54	6.50	0.088	0.106	0.125	0.145	0.165	0.185	0.204	0.224
		2	4.0	14.11	13.41	12.54	11.59	10.59	9.56	8.54	7.53	0.074	0.089	0.105	0.122	0.139	0.155	0.172	0.188
		Avg.	**4.0**	**13.87**	**13.13**	**12.20**	**11.20**	**10.16**	**9.09**	**8.04**	**7.02**	**0.081**	**0.097**	**0.115**	**0.134**	**0.152**	**0.170**	**0.188**	**0.206**

Table A9. BBR test data for mixtures 17 to 20.

Mix	Test		V_a	Stiffness (GPa) and Test Time								Slope (m-value) and Test Time							
No.	Temp	Rep	(%)	8 s	15 s	30 s	60 s	120 s	240 s	480 s	960 s	8 s	15 s	30 s	60 s	120 s	240 s	480 s	960 s
17	-06 C	1	3.4	14.79	13.77	12.57	11.33	10.09	8.87	7.71	6.61	0.105	0.122	0.140	0.158	0.176	0.195	0.213	0.231
		2	3.3	17.20	16.13	14.84	13.49	12.11	10.73	9.40	8.13	0.094	0.111	0.129	0.148	0.166	0.185	0.203	0.222
		Avg.	**3.3**	**15.99**	**14.95**	**13.71**	**12.41**	**11.10**	**9.80**	**8.55**	**7.37**	**0.100**	**0.116**	**0.135**	**0.153**	**0.171**	**0.190**	**0.208**	**0.226**
	-12 C	1	3.4	15.54	14.92	14.08	13.11	12.04	10.91	9.76	8.61	0.056	0.074	0.093	0.113	0.132	0.152	0.171	0.191
		2	3.3	16.50	15.70	14.73	13.69	12.60	11.50	10.39	9.31	0.073	0.085	0.099	0.112	0.126	0.139	0.153	0.166
		Avg.	**3.3**	**16.02**	**15.31**	**14.40**	**13.40**	**12.32**	**11.20**	**10.07**	**8.96**	**0.064**	**0.079**	**0.096**	**0.113**	**0.129**	**0.146**	**0.162**	**0.179**
18	-06 C	1	4.0	12.42	11.47	10.40	9.33	8.28	7.26	6.30	5.41	0.119	0.133	0.149	0.165	0.181	0.197	0.212	0.228
		2	4.0	12.36	11.50	10.51	9.49	8.47	7.48	6.52	5.62	0.107	0.122	0.139	0.156	0.173	0.189	0.206	0.223
		Avg.	**4.0**	**12.39**	**11.49**	**10.46**	**9.41**	**8.37**	**7.37**	**6.41**	**5.51**	**0.113**	**0.128**	**0.144**	**0.160**	**0.177**	**0.193**	**0.209**	**0.226**
	-12 C	1	4.0	17.83	16.73	15.46	14.17	12.86	11.58	10.33	9.13	0.096	0.107	0.120	0.133	0.145	0.158	0.171	0.183
		2	4.0	15.51	14.72	13.76	12.74	11.67	10.58	9.50	8.45	0.077	0.090	0.105	0.120	0.134	0.149	0.164	0.179
		Avg.	**4.0**	**16.67**	**15.73**	**14.61**	**13.45**	**12.27**	**11.08**	**9.92**	**8.79**	**0.086**	**0.099**	**0.113**	**0.126**	**0.140**	**0.154**	**0.167**	**0.181**
19	-06 C	1	4.2	13.21	12.26	11.13	9.95	8.77	7.61	6.51	5.49	0.109	0.129	0.150	0.172	0.193	0.215	0.236	0.258
		2	4.0	13.29	12.33	11.24	10.14	9.04	7.98	6.96	6.01	0.109	0.124	0.140	0.156	0.172	0.188	0.204	0.220
		Avg.	**4.1**	**13.25**	**12.29**	**11.18**	**10.04**	**8.91**	**7.80**	**6.74**	**5.75**	**0.109**	**0.126**	**0.145**	**0.164**	**0.183**	**0.201**	**0.220**	**0.239**
	-12 C	1	4.2	8.13	7.74	7.27	6.76	6.22	5.67	5.11	4.57	0.071	0.085	0.100	0.115	0.130	0.145	0.160	0.175
		2	4.0	15.82	15.08	14.19	13.25	12.28	11.29	10.30	9.33	0.072	0.082	0.093	0.105	0.116	0.128	0.139	0.151
		Avg.	**4.1**	**11.97**	**11.41**	**10.73**	**10.00**	**9.25**	**8.48**	**7.71**	**6.95**	**0.071**	**0.083**	**0.097**	**0.110**	**0.123**	**0.136**	**0.149**	**0.163**
20	-06 C	1	4.3	15.35	14.38	13.17	11.87	10.52	9.17	7.87	6.64	0.095	0.116	0.139	0.163	0.186	0.209	0.233	0.256
		2	4.3	13.28	12.34	11.21	10.03	8.84	7.67	6.55	5.51	0.107	0.128	0.150	0.172	0.195	0.217	0.239	0.262
		Avg.	**4.3**	**14.32**	**13.36**	**12.19**	**10.95**	**9.68**	**8.42**	**7.21**	**6.08**	**0.101**	**0.122**	**0.145**	**0.167**	**0.190**	**0.213**	**0.236**	**0.259**
	-12 C	1	4.3	16.87	15.93	14.81	13.64	12.44	11.22	10.03	8.88	0.085	0.098	0.112	0.126	0.140	0.154	0.169	0.183
		2	4.3	17.45	16.71	15.77	14.73	13.63	12.47	11.30	10.14	0.063	0.076	0.091	0.105	0.120	0.134	0.149	0.163
		Avg.	**4.3**	**17.16**	**16.32**	**15.29**	**14.19**	**13.03**	**11.85**	**10.67**	**9.51**	**0.074**	**0.087**	**0.101**	**0.116**	**0.130**	**0.144**	**0.159**	**0.173**

Table A10. BBR test data for mixtures 21 to 24.

Mix	Test		V_a	Stiffness (GPa) and Test Time								Slope (m-value) and Test Time							
No.	Temp	Rep	(%)	8 s	15 s	30 s	60 s	120 s	240 s	480 s	960 s	8 s	15 s	30 s	60 s	120 s	240 s	480 s	960 s
21	-06 C	1	3.8	16.17	15.37	14.40	13.35	12.26	11.14	10.02	8.93	0.074	0.087	0.101	0.116	0.130	0.145	0.159	0.173
		2	3.8	15.14	14.45	13.63	12.77	11.89	11.00	10.11	9.23	0.070	0.079	0.088	0.098	0.107	0.117	0.126	0.136
		Avg.	**3.8**	**15.66**	**14.91**	**14.01**	**13.06**	**12.08**	**11.07**	**10.07**	**9.08**	**0.072**	**0.083**	**0.095**	**0.107**	**0.119**	**0.131**	**0.143**	**0.155**
	-12 C	1	3.8	20.46	19.60	18.57	17.46	16.30	15.11	13.91	12.71	0.062	0.072	0.082	0.093	0.103	0.114	0.124	0.135
		2	3.8	19.67	18.90	17.95	16.90	15.78	14.61	13.42	12.23	0.058	0.069	0.081	0.093	0.105	0.116	0.128	0.140
		Avg.	**3.8**	**20.07**	**19.25**	**18.26**	**17.18**	**16.04**	**14.86**	**13.66**	**12.47**	**0.060**	**0.070**	**0.082**	**0.093**	**0.104**	**0.115**	**0.126**	**0.137**
22	-06 C	1	3.8	11.56	10.96	10.23	9.44	8.63	7.81	7.00	6.21	0.075	0.089	0.103	0.118	0.132	0.147	0.162	0.176
		2	3.8	11.84	11.24	10.51	9.75	8.95	8.14	7.33	6.55	0.075	0.088	0.101	0.115	0.129	0.142	0.156	0.169
		Avg.	**3.8**	**11.70**	**11.10**	**10.37**	**9.60**	**8.79**	**7.98**	**7.17**	**6.38**	**0.075**	**0.088**	**0.102**	**0.116**	**0.131**	**0.145**	**0.159**	**0.173**
	-12 C	1	3.8	15.38	14.73	13.95	13.10	12.20	11.28	10.34	9.41	0.063	0.073	0.085	0.097	0.109	0.121	0.132	0.144
		2	3.8	15.72	14.99	14.09	13.12	12.10	11.05	10.00	8.96	0.069	0.082	0.096	0.110	0.124	0.138	0.152	0.166
		Avg.	**3.8**	**15.55**	**14.86**	**14.02**	**13.11**	**12.15**	**11.16**	**10.17**	**9.18**	**0.066**	**0.078**	**0.091**	**0.104**	**0.116**	**0.129**	**0.142**	**0.155**
23	-06 C	1	4.0	14.94	14.16	13.23	12.26	11.27	10.27	9.29	8.34	0.080	0.091	0.104	0.116	0.128	0.141	0.153	0.165
		2	3.6	12.18	11.37	10.45	9.51	8.56	7.64	6.75	5.90	0.100	0.113	0.128	0.142	0.157	0.172	0.187	0.201
		Avg.	**3.8**	**13.56**	**12.76**	**11.84**	**10.88**	**9.92**	**8.96**	**8.02**	**7.12**	**0.090**	**0.102**	**0.116**	**0.129**	**0.143**	**0.156**	**0.170**	**0.183**
	-12 C	1	4.0	13.39	12.79	12.06	11.30	10.50	9.69	8.88	8.07	0.069	0.079	0.090	0.100	0.111	0.122	0.132	0.143
		2	3.6	19.82	19.00	18.01	16.94	15.81	14.66	13.48	12.31	0.062	0.072	0.082	0.093	0.104	0.114	0.125	0.136
		Avg.	**3.8**	**16.61**	**15.89**	**15.03**	**14.12**	**13.16**	**12.17**	**11.18**	**10.19**	**0.066**	**0.075**	**0.086**	**0.097**	**0.107**	**0.118**	**0.129**	**0.139**
24	-06 C	1	4.3	16.68	15.87	14.90	13.87	12.81	11.74	10.68	9.64	0.073	0.084	0.096	0.108	0.120	0.131	0.143	0.155
		2	4.0	12.99	12.30	11.48	10.62	9.72	8.83	7.93	7.07	0.079	0.092	0.105	0.119	0.133	0.146	0.160	0.174
		Avg.	**4.2**	**14.83**	**14.08**	**13.19**	**12.24**	**11.27**	**10.28**	**9.31**	**8.35**	**0.076**	**0.088**	**0.100**	**0.113**	**0.126**	**0.139**	**0.152**	**0.165**
	-12 C	1	4.3	19.22	18.42	17.42	16.30	15.11	13.88	12.62	11.36	0.061	0.074	0.088	0.102	0.116	0.130	0.145	0.159
		2	4.0	19.23	18.47	17.52	16.48	15.36	14.20	13.02	11.83	0.059	0.070	0.082	0.095	0.107	0.119	0.131	0.144
		Avg.	**4.2**	**19.23**	**18.45**	**17.47**	**16.39**	**15.24**	**14.04**	**12.82**	**11.59**	**0.060**	**0.072**	**0.085**	**0.098**	**0.112**	**0.125**	**0.138**	**0.151**

Table A11. Moisture-damage test data for mixtures 1 to 12.

Mix No.	Temperatures		Dry Set Avg.		Conditioned Set Avg.		TSR (%)
	Mixing (C)	Compaction (C)	V_a (%)	S_t (kPa)	V_a (%)	S_t (kPa)	
1	165	146	6.8	1698	6.8	1252	0.74
2	165	146	6.8	2093	6.9	2125	1.02
	146	132	6.4	2010	6.4	1813	0.90
	130	116	6.4	1782	6.4	1530	0.86
3	165	146	6.9	2218	7.0	2232	1.01
	146	132	7.0	1812	7.1	1477	0.82
	130	116	7.4	1840	7.4	1259	0.68
4	165	146	6.9	2052	7.0	1933	0.94
	146	132	6.9	1830	7.0	1578	0.86
	130	116	6.6	1808	6.6	1645	0.91
5	165	146	6.4	3180	6.3	3473	1.09
6	165	146	6.5	3617	6.4	3512	0.97
	146	132	6.8	2963	6.8	2418	0.82
	130	116	6.6	1738	6.5	1790	1.03
7	165	146	6.4	3715	6.4	3398	0.91
	146	132	6.9	3065	6.9	2735	0.89
	130	116	6.7	2163	6.8	2438	1.13
8	165	146	7.0	3480	7.0	3178	0.91
	146	132	7.1	3202	7.1	2663	0.83
	130	116	6.5	3180	6.6	2860	0.90
9	165	146	6.6	3642	6.6	3660	1.01
10	165	146	6.7	4167	6.7	3598	0.86
	146	132	6.1	4375	6.1	3883	0.89
	130	116	6.9	1640	6.9	1600	0.98
11	165	146	6.1	4675	6.1	4463	0.95
	146	132	7.1	4307	7.1	3772	0.88
	130	116	6.4	1790	6.4	2035	1.14
12	165	146	7.3	4540	7.3	3968	0.87
	146	132	7.3	4147	7.4	3213	0.77
	130	116	6.5	3878	6.7	4112	1.06

Table A12. Moisture-damage test data for mixtures 13 to 24.

Mix No.	Temperatures		Dry Set Avg.		Conditioned Set Avg.		TSR (%)
	Mixing (C)	Compaction (C)	V_a (%)	S_t (kPa)	V_a (%)	S_t (kPa)	
13	165	146	7.5	1953	7.4	1867	0.96
14	165	146	6.7	2208	6.7	1960	0.89
	146	132	6.8	2168	6.8	1448	0.67
	130	116	6.9	1882	7.1	1613	0.86
15	165	146	7.0	2082	6.9	1858	0.89
	146	132	7.1	2057	7.0	1382	0.67
	130	116	7.4	1862	7.4	1625	0.87
16	165	146	7.6	2013	7.5	1592	0.79
	146	132	6.3	1890	6.3	1080	0.57
	130	116	6.8	1922	6.7	883	0.46
17	165	146	7.7	3058	7.4	3263	1.07
18	165	146	7.1	3272	7.1	3153	0.96
	146	132	6.6	3205	6.5	2943	0.92
	130	116	6.7	3218	6.7	2535	0.79
19	165	146	6.6	3618	6.4	3245	0.90
	146	132	6.8	3460	6.7	2955	0.85
	130	116	6.9	2247	6.9	1460	0.65
20	165	146	7.0	3763	6.9	3253	0.86
	146	132	6.8	3487	6.8	2478	0.71
	130	116	7.8	2925	7.8	1942	0.66
21	165	146	7.2	3942	7.2	3986	1.01
22	165	146	7.0	3633	6.9	3478	0.96
	146	132	6.7	4120	6.7	3550	0.86
	130	116	6.1	2413	6.1	2397	0.99
23	165	146	6.2	3698	6.2	3795	1.03
	146	132	6.8	4360	6.8	3878	0.89
	130	116	6.3	4402	6.3	3777	0.86
24	165	146	6.7	4388	6.8	3958	0.90
	146	132	6.3	4372	6.3	3318	0.76
	130	116	7.2	3950	7.3	3063	0.78

Figure A1. Workability test data for mixtures 1 to 4.

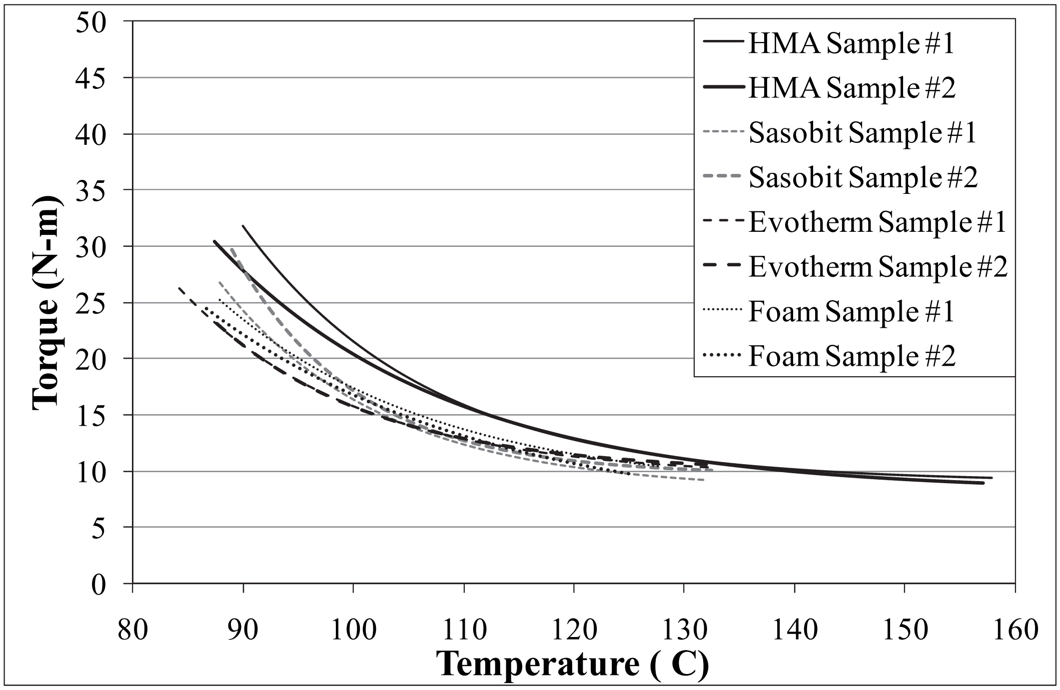


Figure A2. Workability test data for mixtures 5 to 8.

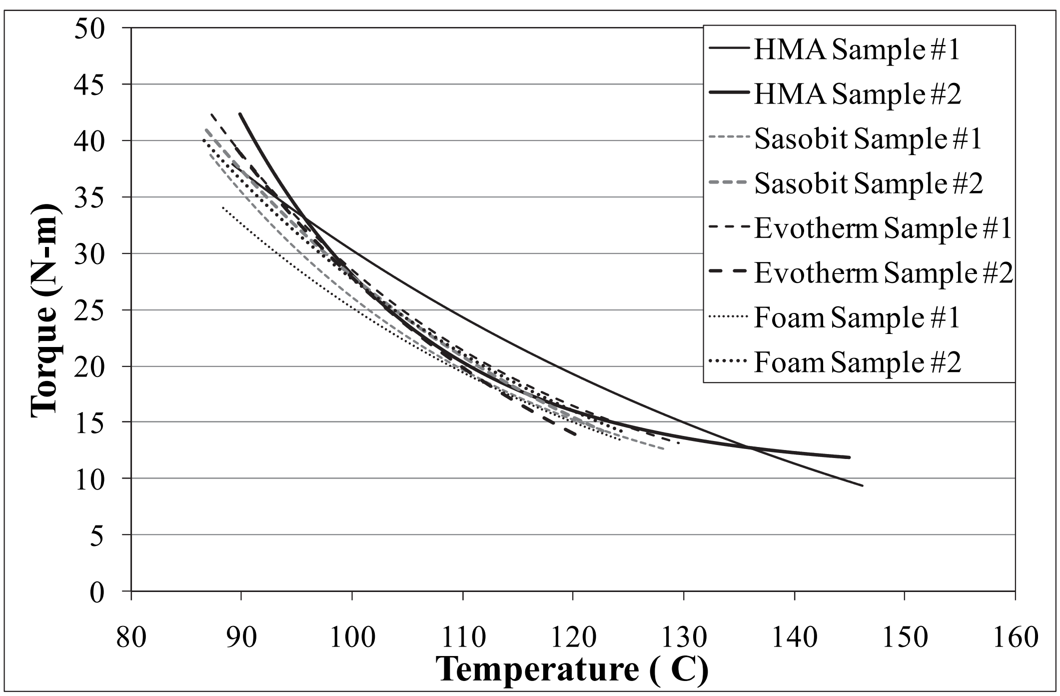


Figure A3. Workability test data for mixtures 9 to 12.

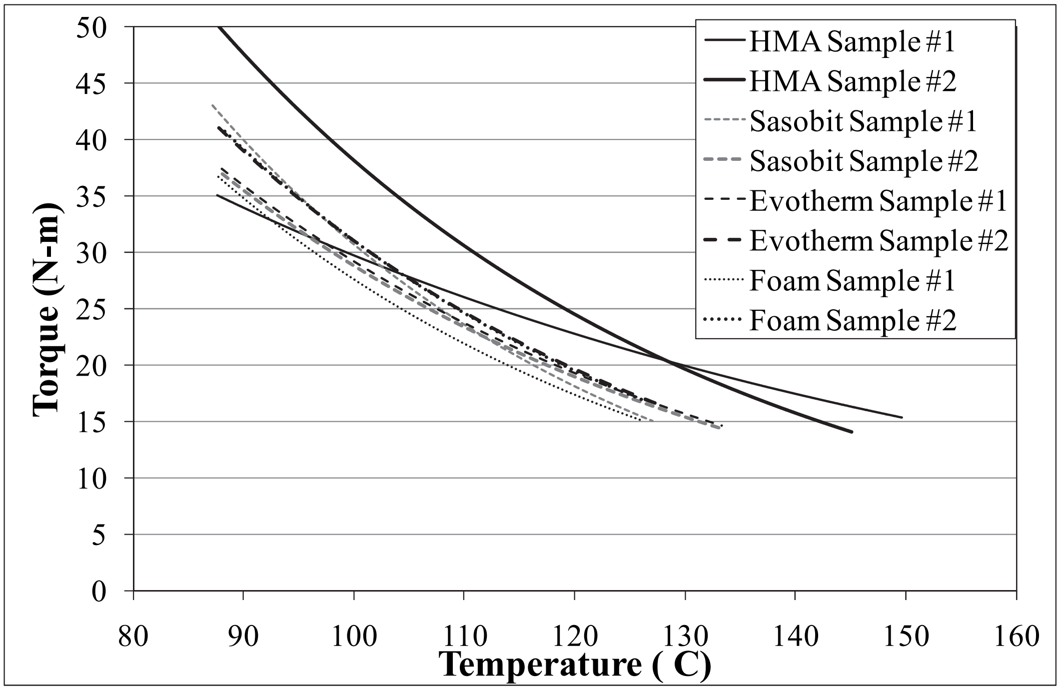


Table A13. Regressions of workability data for mixtures 1 to 12.

Mix No.	Rep	Regression Data			
		a	b	c	R^2
1	1	9.03	14179	0.0594	0.89
	2	8.14	3724	0.0486	0.92
2	1	8.28	24996	0.0684	0.90
	2	9.55	246081	0.0882	0.80
3	1	8.91	3716	0.0540	0.89
	2	9.86	13968	0.0666	0.85
4	1	8.15	3657	0.0504	0.87
	2	5.56	1137	0.0396	0.90
5	1	9.10	269	0.0162	0.88
	2	10.66	17903	0.0594	0.77
6	1	5.29	1642	0.0378	0.87
	2	1.39	762	0.0270	0.88
7	1	5.32	1748	0.0360	0.84
	2	2.14	1136	0.0306	0.88
8	1	0	533	0.0252	0.86
	2	0	695	0.0270	0.88
9	1	0	143	0.0133	0.80
	2	0	517	0.0221	0.90
10	1	0	679	0.0270	0.81
	2	0	337	0.0216	0.75
11	1	0	334	0.0216	0.75
	2	0	453	0.0234	0.81
12	1	0	436	0.0234	0.81
	2	0	477	0.0232	0.78

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
February 2012

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Evaluation of Warm-Mix Asphalt Technologies for Use on Airfield Pavements

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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Mississippi State University, Department of Civil and Environmental Engineering, 501 Hardy Road, 235 Walker Hall, P.O. Box 9546, Mississippi State, MS 39762-9546

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/GSL TR-12-3

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Headquarters, US Air Force Civil Engineer Support Agency
139 Barnes Avenue, Suite 1
Tyndall Air Force Base, FL 32403-5319

10. SPONSOR/MONITOR'S ACRONYM(S)
AFCESA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Revised December 2013

14. ABSTRACT
From May 2010 to September 2010, researchers of the US Army Engineer Research and Development Center and Mississippi State University evaluated the performance of different warm-mix asphalt (WMA) mixtures for their use for airfield pavements. The performance of mixtures produced using different WMA technologies was compared to the performance of the same mixtures produced at hot-mix asphalt (HMA) temperatures. Studied were permanent deformation, durability, non-load associated cracking, moisture damage, and workability.

Evaluated were Evotherm™ 3G, Sasobit®, and foamed asphalt. Two aggregates, crushed chert gravel and crushed limestone, were used. The base binder was PG 67-22 from a single refinery. Three reclaimed-asphalt pavement (RAP) contents were used (0, 25, and 50%) to study the incorporation of higher percentages of RAP in WMA than allowed in HMA.

Results indicated WMA is a viable product for airfield pavement surface mixtures. However, rutting from traffic and moisture-damage susceptibility must be addressed. Adding RAP to the mix could help, but also could reduce low-temperature performance and durability. Findings suggest WMA with RAP is less susceptible to low-temperature performance problems than HMA with RAP. However, it's not possible to translate the lab results for durability or workability to field performance.

Two engineering technical letters (ETLs) and a guide specification were developed from this study. The first, ETL 11-3, was published in August 2011 and provides general information and guidance. The second ETL and the guide specification, both under review, provide more specific guidance on design and construction of airfield pavements using WMA.

15. SUBJECT TERMS

Warm-mix asphalt	Laboratory performance	Low-temperature cracking
Airfield pavements	Rutting	Durability
	Moisture susceptibility	Workability

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified		84	